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A Survey on Actuators-Driven Surgical Robots

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Abstract

Robot-assisted surgeries have been integrated and leading to a paradigm shift in surgical fields. With the emergence of Minimally Invasive Surgery (MIS), especially Natural Orifice Transluminal Endoscopic Surgery (NOTES), there are various benefits such as a minimization of side effects, enhancement of precise surgical procedures, and faster recovery after the surgery that patients can take from. However, in order to effectively employ and exploit surgical robots, numerous technical challenges need to be addressed. Among these, actuators play a vital role. To provide deeper understanding on current actuators-driven surgical robot, this study will comprehensively review on four main types of transmission systems namely cable-driven mechanism, flexible fluidic actuators, smart material actuators, and magnetic actuators, in terms of conceptual designs, modelling, and control as well as their advantages and disadvantages. Profound discussions and recommendations for the future of actuators-driven surgical robots will be also pointed out to give the roadmap in the surgical field.

Key Terms: *Minimally Invasive Surgery (MIS), NOTES system, surgical robots, cable-driven robots, flexible fluidic actuators, smart material actuators, magnetic actuators.*

I. Introduction

Robots have been revolutionizing our life in the different ways for a long time. Apart from extensively being used in industrial areas, the advanced robots are now also creeping into other various sectors such as education, aerospace, and agriculture. In addition, over the course of the last few decades, robots have been integrated into clinical rooms to replace the conventional surgical procedure (open surgery) by minimally invasive surgery (MIS) procedure which provides numerous benefits like shortened hospital time, minimized post-surgery effects, better cosmetics, and reduced patient's discomforts [1]. In general, MIS procedure can be categorized into several types such as extraluminal, intraluminal, transluminal, and hybrid approaches. An overview of the development for MIS is summarized in Fig. 1.

With the support of modern technology and science advancements such as medical imaging, computer assistance and design, MIS has gained significant success and popularity. However, there are many inherent obstacles that need to be dealt with. In the body's confined space, it is challenging to precisely accomplish the surgical tasks without using instruments that are adequate manoeuvrability, triangulation, and flexibility. In addition, the lack of position and haptic feedback is much more challenging. Natural Orifice Transluminal Endoscopic Surgery (NOTES) is a new paradigm that makes use of natural orifices to access the peritoneum for surgery without leaving visible scars. Current technologies for NOTES system limit it to transoral, transvaginal, and transanal avenues of access, but with miniaturization even more may be possible.

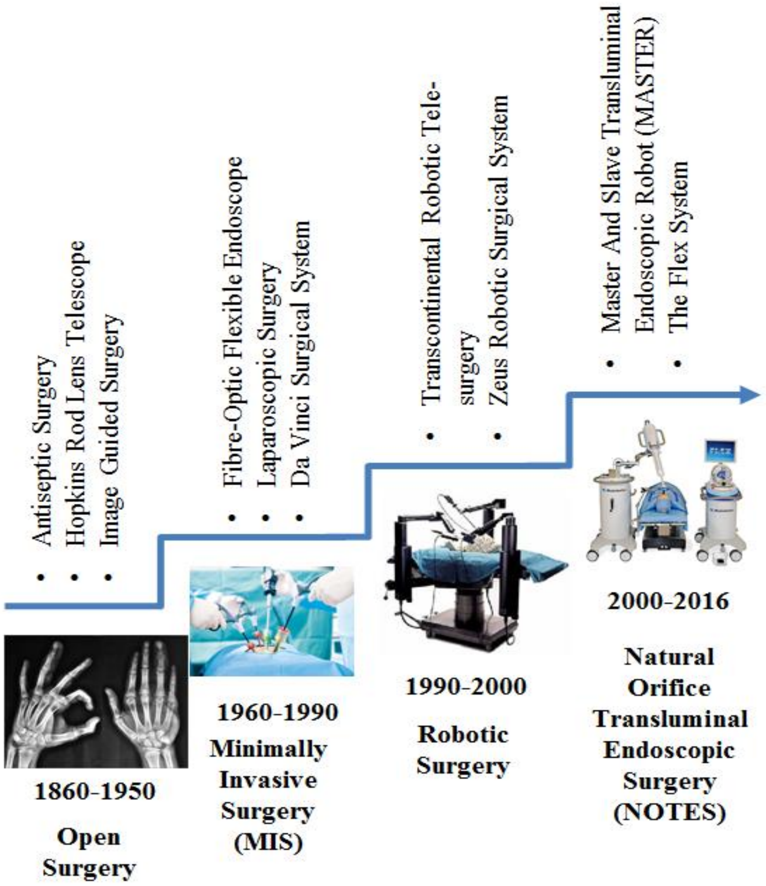


Fig. 1. Some major milestones in surgical robotic development with illustrated systems

In order to provide motion and force for devices to manipulate the tissues or pass through gastrointestinal (GI) tract to examine the organs, the conventional design concept usually embeds ferromagnetic actuator to actuate the end effector. However, this approach is inapplicable for surgical cases due to bulkiness, heaviness, and large size. For surgical robots, the power supplies and actuators are usually installed far away from the end effector and surgical sites, leading to simplicity, miniature, and light weight for the instruments once they are inside the human body (see Fig. 2).

For NOTES procedures, the surgical arms must be small and flexible in order to adapt with natural human orifices and complex GI tract. Compared to embedded ferromagnetic approach where the actuators are directly installed at joints, the remote transmission system like cable actuator will reduce the induced force that plays an important role in surgery. So, the requirement of small, flexible, and high payload for actuators-driven surgical robots needs to be met. Up to date, several actuators have been used as the main mode of motion and force transmission in surgical robots such as cable system (tendon, wire), fluidic actuators, and magnetic actuator. Smart materials like shape memory alloy (SMA) or piezoelectricity are also preferred. However, a critical review on these modes of transmission is still lacking in the literature. In this paper, different actuators-driven surgical robots will be comprehensively reviewed in terms of design concept, application, modelling, and control. In addition, the analysis of their advantages and disadvantages as well as the discussions and recommendations for possible future research directions will be also given.

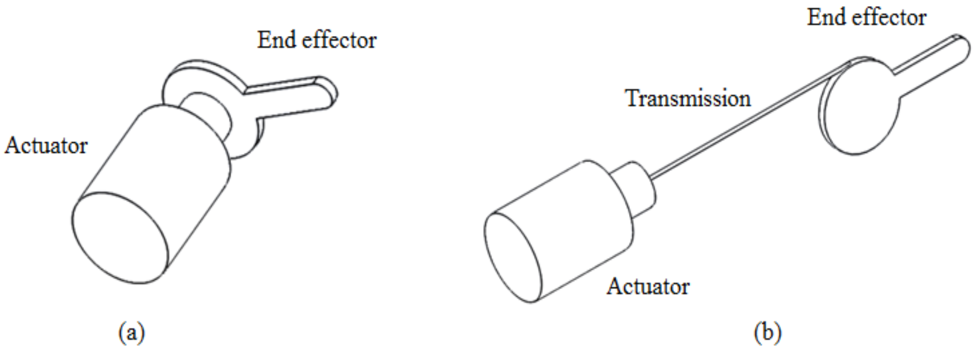


Fig. 2. Different configurations for actuator-driven surgical robots with (a) Actuators is directly installed at the end effector and (b) Actuator is put far away from the end effector

The rest of this review paper will be organized as follow. In the section 2, some typical surgical robotic systems will be described. Section 3 analyses the four main kinds of actuators, namely cable, flexible fluidic, smart material and magnetic actuators followed by the discussions, suggestions, and comparisons. Finally, the conclusions with discussions on the future direction of actuator-driven surgical robot will be drawn in the section 4.

II. Typical surgical robotic systems

Based on the applied tools, surgical robotic systems can be divided into two main groups: laparoscopy and flexible endoscopy [2]. Take laparoscopic surgery into consideration, the instruments are usually rigid and long shaft with cameras integrated for visual display, which all enter the human body via incisions in the abdominal walls. In contrast, flexible endoscopy utilizes flexible endoscope with integrated camera and tool channels to allow flexible arms to access the human body via natural orifices or small incision. In the most common embodiment, instruments emerge from the tip of the endoscope into the camera's field of vision. These instruments are similar to those used in laparoscopic surgery, such as tissue graspers, electrocautery devices, and wire loops. Some typical laparoscopic systems have been commercialized such as Da Vinci surgical system [3], RAVEN and MiroSurge robot [1, 4], FreeHand and Telelap ALF-X teleoperated surgical system [1], NeroArm and MrBot robot [1]. For illustration, Da Vinci surgical system which is the most famous platform will be introduced.

Da Vinci surgical system which is shown in Fig. 3 from Intuitive Surgical Inc. is the only surgical robot with a thousand systems installed all over the world. It consists of surgeon console where the surgeon can sit and remotely control the surgical tools, patient-side cart which contains the robotic arms to hold and exchange the tools easily, vision system for observation enhancement during operation period, and EndoWrist instruments which are driven by cable pulley system and can provide up to 7 degrees of freedom (DOFs) with 90^0 of articulation. Initially, Da Vinci Surgical System was cleared for laparoscopy and is now cleared by FDA for other different procedures [5, 6]. Although Da Vinci surgical system have been gaining the huge success since initialized, it still presents some limitations like high-associated cost, the heaviness and bulkiness, lack of position and force feedbacks for surgeon and sometimes inefficiency in flexibility because of rigid articulated tools, which is addressed by flexible endoscopy.

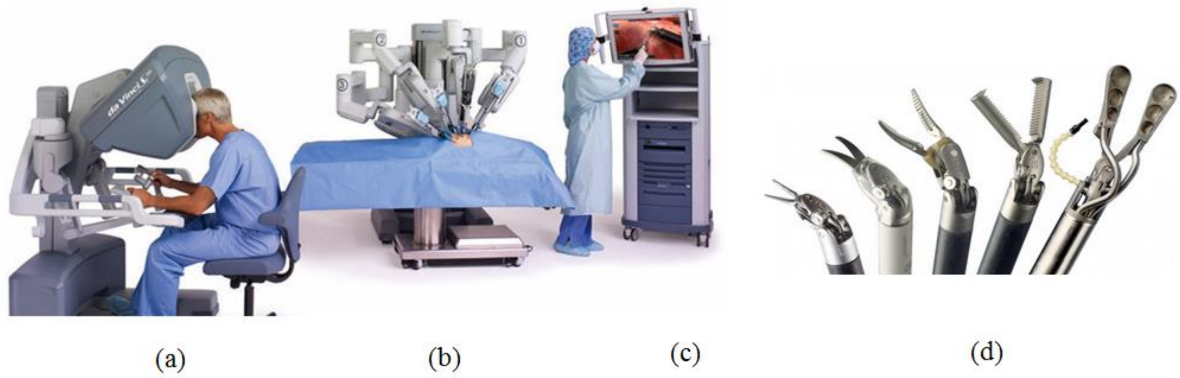


Fig. 3. Da Vinci Surgical System (Intuitive Surgical, Inc., Sunnyvale, CA)

(a) Surgical Console; (b) Patient Side-Cart; (c) 3-D vision; (d) EndoWrist instruments

To limit the port-site complications, reduce the discomforts, and eliminate the scars from laparoscopy, Natural Orifice Transluminal Endoscopic Surgery (NOTES) has been proposed. With NOTES, robotic arms are implemented in flexible endoscope to increase their effectiveness and safety, as well as to augment their therapeutic capabilities. NOTES approach allows flexible tools to access the human body via natural orifices such as mouth, anus, vagina, and then follow the bending, tiny tract to do certain surgical tasks. The devices intended for NOTES are often flexible tubes integrated with instruments and visual systems inside. There is a diversity of surgical systems for NOTES. For example, Master and Slave Transluminal Endoscopic Robot MASTER system [7], Medrobotics Flex System [8], Viacath [9], USGI Cobra and R-Scope [10], Scorpion shaped robot [11], IREP [12]. In this section, MASTER system will be presented as a typical example of NOTES.

The MASTER system has been developed at Nanyang Technological University and commercialized under the company EndoMaster Pte Ltd for NOTES and Endoscopic Submucosal Dissection (EDS) applications (See Fig. 4). It utilizes tendon-sheath mechanisms-driven flexible robotic manipulator to actuate multi DOFs of the robotic arms integrated at the tip of a flexible endoscope. To operate the robot during operation, an endoscopist and a robotic operator are required. The MASTER robot consists of a master console, a microprocessor and actuator housing, and a slave manipulator. The slave manipulator contains a camera to provide vision feedback to the surgeon and two flexible robotic arms including a grasper with the size of about 3.7mm and a cauterizing hook with the size around 2.8mm to perform surgical procedures. The master console maps the natural DOFs for rotation and translation motion of the human's arms to the slave manipulator via a motor housing. By attaching suitable sensors, this console can sense the movement from surgeon and produce a rough haptic feedback to the surgeon. The microprocessor, which is connected to the motion controller, can interpret the signals from encoders and loadcells located at the proximal end. The actuator housing, which contains tendon-sheath mechanisms, rotating drums, loadcells, and motors, is an intermediate interface between the actuator and the slave manipulator. The actuator housing receives the signals from the master console and directly drives the slave manipulator to carry out the necessary treatments for patients such as cutting and suturing. Clinical demonstrations have been performed, such as NOTES liver resection and endoscopic submucosal dissection (ESD).

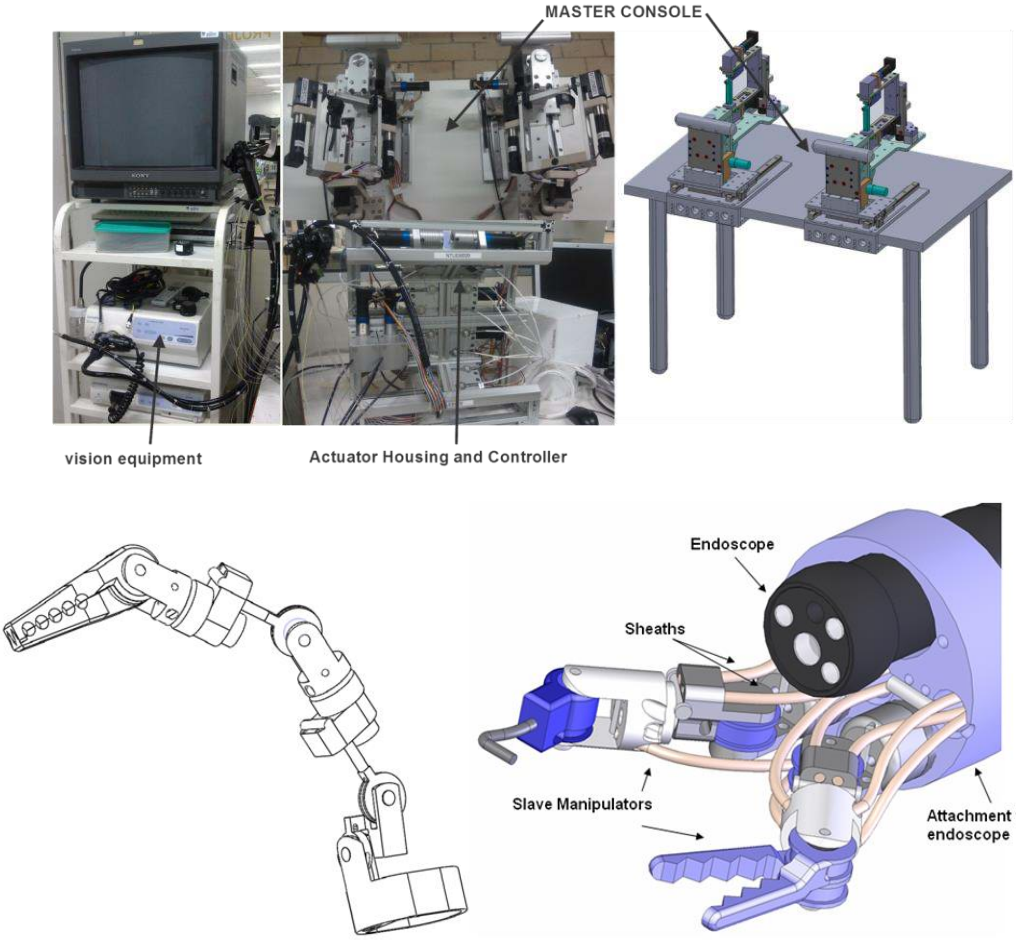


Fig. 4. MASTER system including actuator housing, microprocessor, master console, and slave manipulator

III. Review on different actuators-driven surgical robots

In this section, an overview for current development of various transmission modes used in surgical applications will be given in order to fill in small gaps in the literature. We provide a brief perspective on the actuator technologies that are shaping the future research of both rigid and flexible surgical robots.

A. Cable actuator

Thanks to the development of flexible transmission systems, it is able to place the joints and application points far away from the actuator sites. Cable-driven actuation is capable of conveying position/force from external actuators to remote sites via flexible tubes or pulleys. This type of actuation can across confined space and manipulate objects in complex environments. According to the applications, the cables are made of different materials from stainless steel [3, 13-15], polyethylene [16], to super-elastic materials (NiTi) [17, 18]. The robot's size is also diversified ranging from 2.4mm [19] to 23mm [20]. Due to their lightweight, simplicity, bio-compatibility, safety, and flexibility cable systems have been used for various surgical robotic systems such as Da Vinci surgical system [3, 13, 14], endoscopes [14, 21], Medrobotics Flex System [8, 22, 23], MASTER system [24, 25], and Viacath system [9]. The following contents will analyse the conceptual designs, modelling, control problems, advantages, and disadvantages of cable actuation-driven surgical robots.

Conceptual design

In general, there are two main types of cable (tendon, wire) actuator configurations namely tendon-routed sheath and cable-routed pulley as shown in Fig. 5. Normally, one side of cable is attached to the actuator and the other side is connected to the actuated joint. Once the cable is pulled at one side, it will slide inside the sheath or over the pulleys and transmit the position/force to the other side.

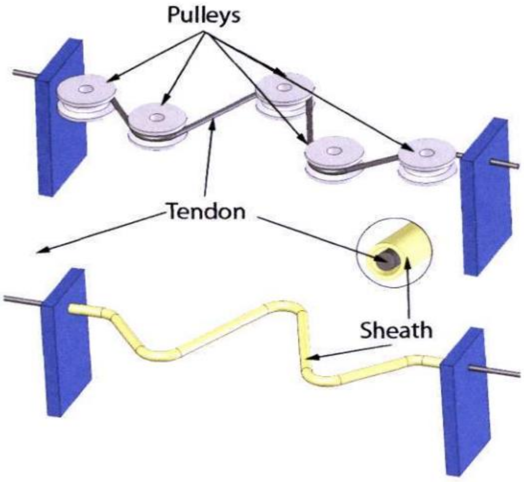


Fig. 5. Tendon-routed pulley (upper panel) and tendon-routed sheath (lower panel) [26]

Tendon-sheath mechanism (TSM) basically includes a hollow coil wire as a sheath and an inside cable as a tendon. The TSM not only operates in small working areas but also passes through long narrow and tortuous paths, and allows for simpler mechanical design as well as less spatial constraints on the operation environment. In addition, it does not require high electrical power or actuator to operate the joints. The need of flexible actuation with low bulkiness, simple design, high maneuverability, small size, and light weight has made the TSM a very potential candidate for the power transmission in surgical systems [26]. Thanks to many advantages, it has been widely used in many robotic applications and flexible surgical devices [9, 24, 27-29]. However, high friction force and backlash hysteresis are still the underlying problems in the use of TSM.

On the other hand, tendon-routed pulley uses pulleys to support the tendon and transmit the force/motion to the remote joint. The main advantages of this design compared to the TSM are that it can provide higher force due to minimized friction effects and more predictable control. Although tendon-routed pulley offers advantages over the TSM [30-33], its rigidity and bulkiness result in the heavy systems and complexity. Hence, the use of tendon-routed pulley is limited in some surgical applications, especially in NOTES systems.

For the tendon-driven mechanisms, there are three different modes for controlling one DOF. They can be categorized into n, n+1, 2n configurations where n is the number of DOFs. Fig. 6(a) and 6(b) represent for the case n actuators drives n DOFs while Fig. 6(c) denotes 2n actuators regulates n DOFs [34-36].

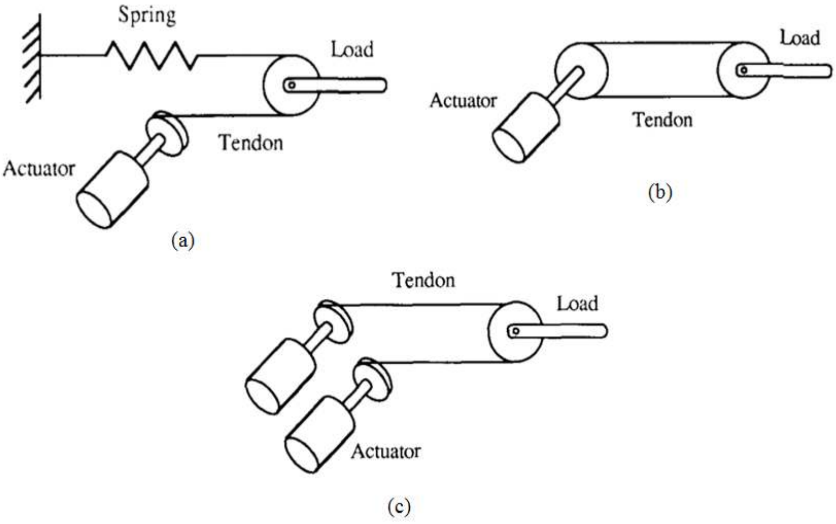


Fig. 6. Actuation methods for tendon driven mechanisms [34]

It is commonly seen in many surgical applications for the case of n actuators drives n DOFs thanks to the ease of implementation [37-39]. In this configuration, both ends of the tendons are tied into two opposite sides of the motors. Whenever the motors move either clockwise or anti-clockwise, the manipulators will rotate with the same direction.

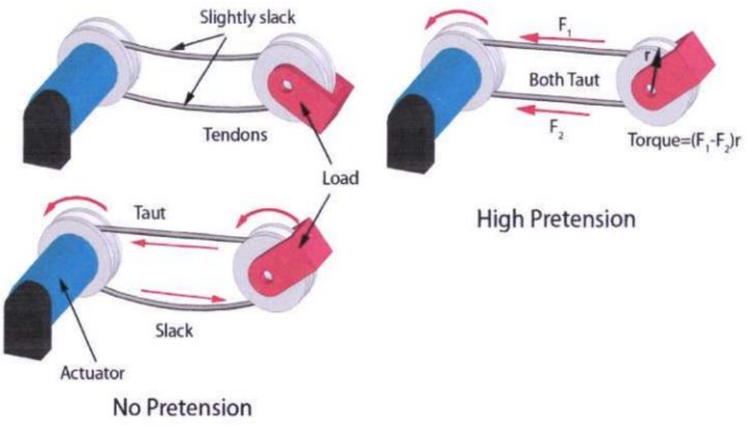


Fig. 7. No and high pretension in tendon actuation [26]

The main inherent drawback is a need for the tendon's high pretension to reduce backlash and hysteresis. If the tendons are not taut, when it changes the rotation direction, there is a redundant move of the actuator needed to compensate the slack before the joint can start moving (see Fig. 7). As a result, this design is not suitable for high speed or quick response applications. Furthermore, with the presence of high pretension, the pulling force must be excessive to overcome the contraction force followed by high friction force and degraded systems.

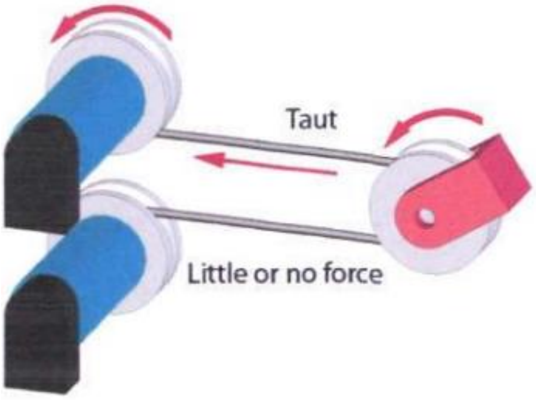


Fig. 8. Two actuators for 1 DOF actuation [26]

By contrast, using 2n actuators to drive n DOFs can minimize both the slack and the contraction force by adding one more motor while the other is pulling the tendon (see Fig. 8). Although this mode can enhance the system's performances, the actuator's housing will become bulkier that leads to the extra cost and large size of the surgical system.

Cable-driven laparoscopic devices

The laparoscopic instruments found in the literature are only cable driven like EndoWirst [14], MICA versatile instruments [40, 41], and SPRINT [42] or tendon-sheath actuated such as system in [43], or using both of them as hybrid instrument [44].

The Da Vinci is one of the most well-known commercialized surgical robotic systems, approved by the US Food and Drug Administration (FDA) in 2000. It consists of surgeon console, patient-side cart, EndoWrist Instruments, and vison system [45]. The Da Vinci slave manipulator has up to 7 DOFs (3 for orientations, 3 for translations, and one for grip) [3]. In its design, a majority of disks or vertebrae is stacked together to build the wrist mechanism. The multiple cables that can extend from the proximal vertebra to the intermediate or to distal vertebra are used for actuation. The holes or grooves with small or large radius can be seen as actuator mechanism (see Fig. 9).

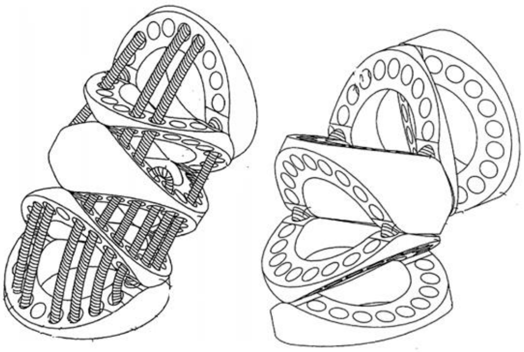


Fig. 9. The cable paths and bending mechanism [13]

In basic designs, instrument's tip is controlled by looped cables and pulley systems, providing 2 rotational DOFs in two perpendicular planes as shown in Fig. 10. There will be no backlash seen when the cables are fully tensioned and the EndoWrist can be considered as a stiff system since the steel cables and rigid links are highly stiff.

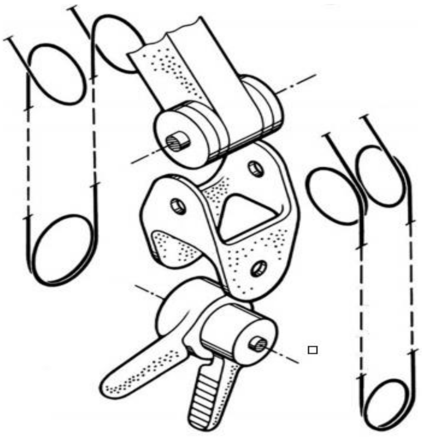


Fig. 10. The view of EndoWrist with cables and pulleys [14]

MIRS system which is a 3-DOF versatile instrument driven by cable including 2-DOF wrist and 1-DOF functional end is introduced in [40, 41]. The articulated joint, as depicted in Fig. 11, is mostly similar to universal joint with interacting axes. The driven cables are always tangent to the joint's pulleys keeping their lengths unchanged. While one middle point of cable is attached to the distal end of the joint, the proximal ends are connected to the motors.

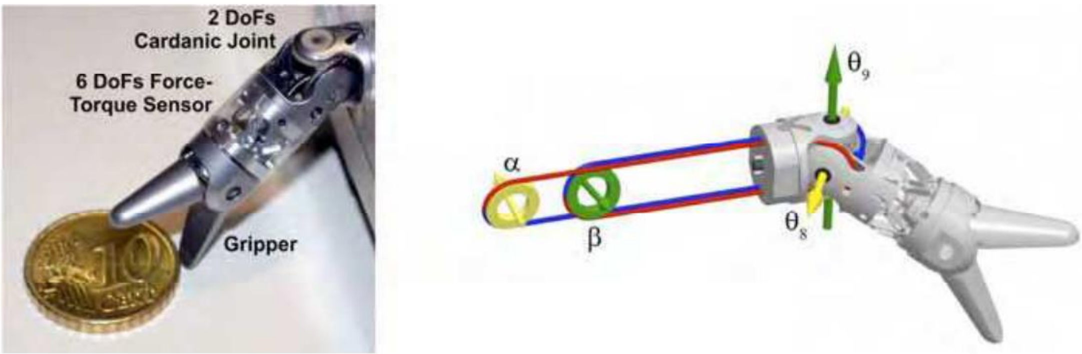
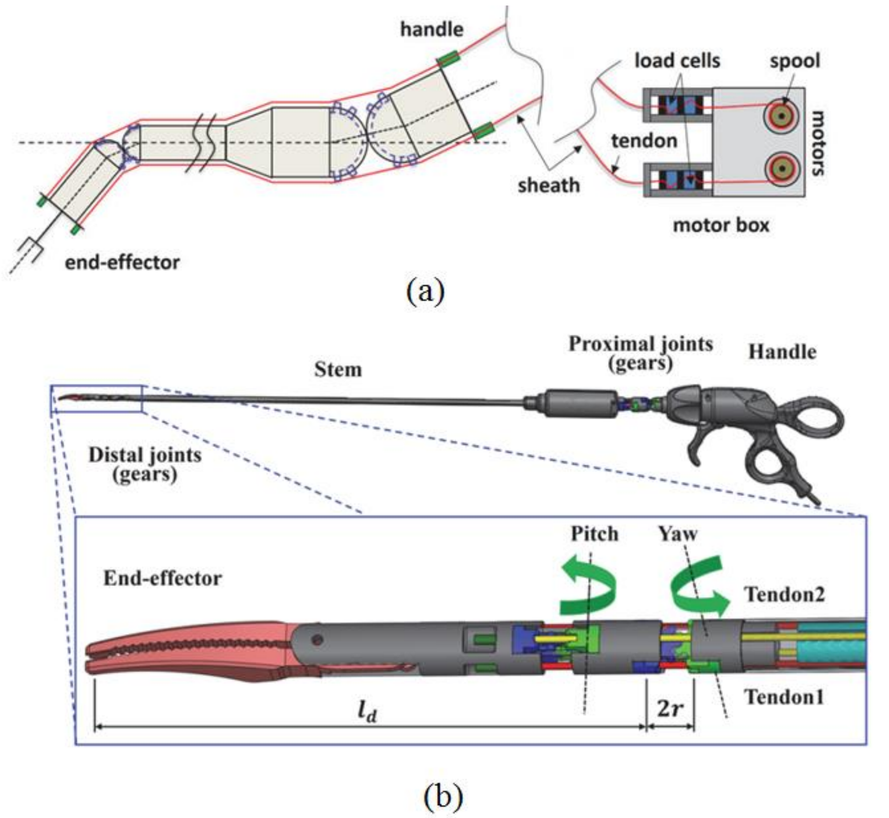


Fig. 11. The prototype and cable layout [41]

A prototype with the total length of 548mm, the diameter of 6.5mm, and 7-DOF force/torque sensor integrated was built and tested. Although the current motor model limits the end effector articulation to 17.4^0, but the gripping force can be obtained at 10N which is efficient for surgery.

Kim et al. [44] presented a hybrid instrument for laparoscopic surgery using tendon-gear mechanism for end-effector's dexterous movements and flexible tendon-sheath transmission to compensate the tendon elongation during the surgical operation. Tendon-gear mechanisms (see Fig. 12 (a)) provide two more DOFs (pitch and yaw) for the end-effector that is higher than conventional instruments [46]. Each joint in articulated instrument has two interlocking gears with four tunnel-like tendon sheaths in total. When the handle is angled, the proximal end will rotate, thanks to a pair of interlocking gears, one side of tendon will flex, while the other side will slacken.



(a)

(b)

Fig. 12. Mechanical structure of hand-held instrument (a) Systematic view of the hybrid tool with tendon-gear and tendon-sheath mechanism, (b) Detail presentation of end-effector [46]

Since the tendon cannot strengthen without applying external force, so the torque generated from proximal joint's angulation is transferred to the distal joint making it rotates in the same direction. In terms of operation theory, the hybrid instrument is similar with the traditional articulated tools. However, the distinct point is that, in conventional method, the output loss will be compensated by surgeon, while the two servomotors and tendon-sheath mechanism are responsible for this duty in hybrid handheld.

Cable-driven flexible endoscopic devices

Tendon-pulley system and tendon-sheath mechanism are massively exploited in flexible endoscopic devices. Some notable systems such as Endo-Periscope using stainless steel cables [21], Medrobotics Flex System using polyethylene cable [8, 22, 23], ViaCath using TSM, MASTER using TSM, Scorpion shaped endoscopic robot using TSM, STRAS system using TSM [9, 11, 24, 47], robotic arm of Imperial College using NiTi cable [48], and CUHK robotic arm using combination of tendon-sheath mechanism and stainless steel cable [49] are available in the literature.

Paul Breedveld et al. [21] introduced four generations of a new endoscope namely Endo-Periscope which has 2 bending DOFs and it is inspired by the tentacles of squid. For the two first versions, they made use of compression spring in lieu of spine mechanism. In order to fix the cables in their positions, the ring-spring was designed with the combination of high torsion stiffness and low asymmetric bending stiffness (see Figs. 13 and 14). The bending can be accomplished by controlling the cable length. Regarding the two next generations, for the ease of cost and commercialization, the ring-spring was replaced by standard coil spring. Otherwise, the cable-mechanism was used and the principle of spatial parallelogram-mechanism was applied for the control of steerable tip (see Fig. 15).

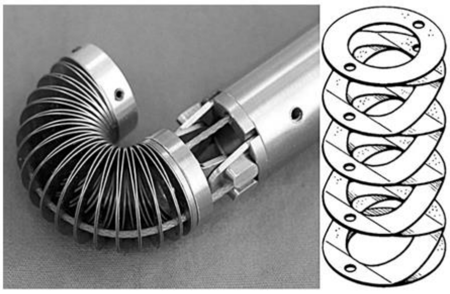


Fig. 13. Steerable tip and ring-spring version I with diameter of 15 mm [21]

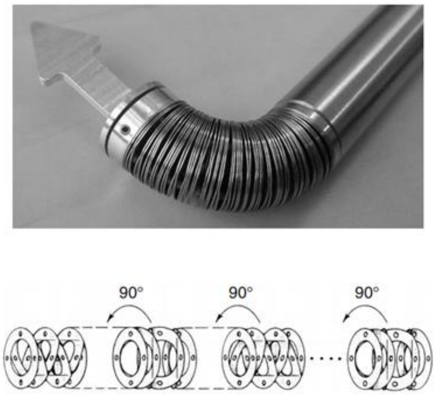


Fig. 14. Steerable tip and ring-spring version II with the diameter of 12 mm [21]

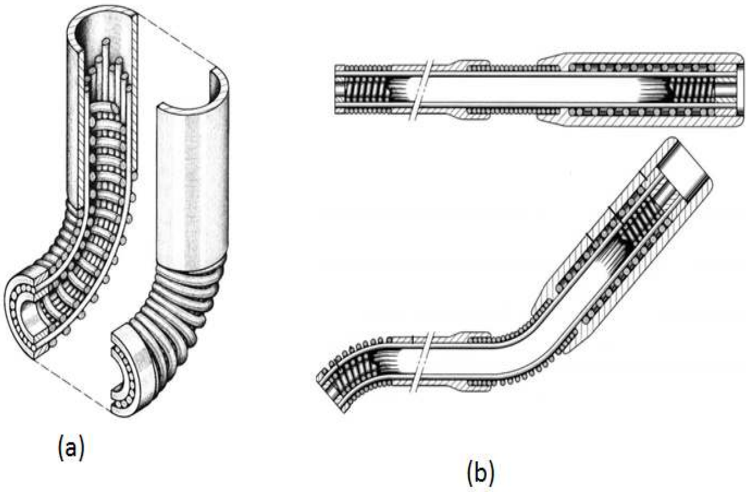


Fig. 15. Detailed design of Endo-Periscope III (a) Cross section of the tip Endo-Periscope III and (b) Parallelogram-mechanism in cross section view [21]

One of other robotized systems intended for NOTES is ViaCath robot that includes the two 7-DOF slave manipulators with the interchangeable tool tips. If the rotation and translation DOFs outside are taken into account, the total number of DOFs is nine in which the DOFs from three to nine are driven by pull-pull cable-conduit pairs (see Fig. 16). The major challenge to the articulated joint section is to prevent the cables from changing paths while actuation. If the cables are not constrained, they will find the shortest way to go causing the 'snap-through'. In order to overcome this problem, the Accura 25 resin cable guides are designed to manage the cables in predetermined fashion (see Fig. 17).

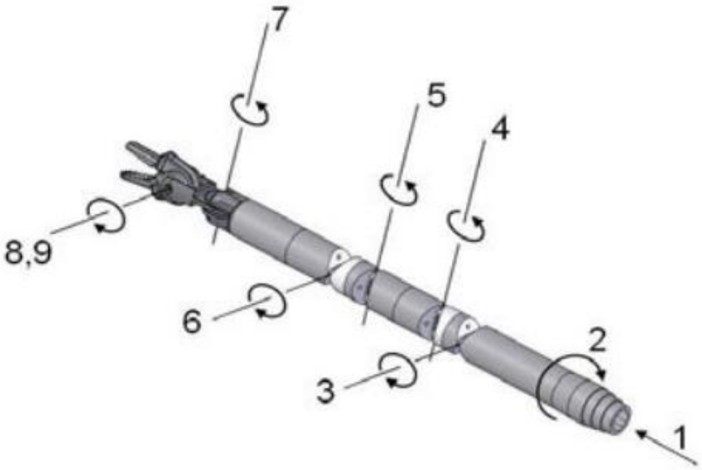


Fig. 16. The slave manipulator of ViaCath [9]

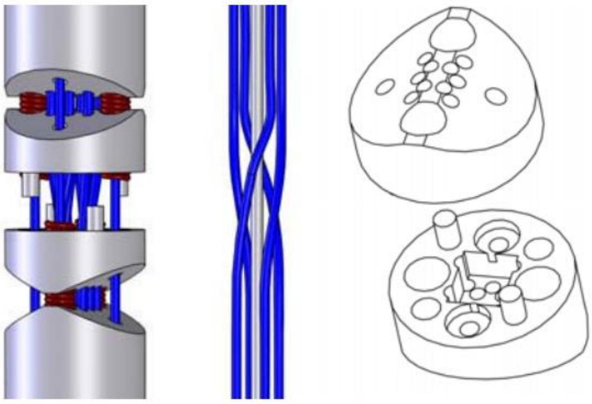


Fig. 17. Cable guides for controlling the paths [9]

A highly articulated robotic probe (HARP) with novel steering mechanism was proposed in [16]. The HARP comprises of two rigid cylindrical concentric tubes articulated by four cables in total and connected by spherical joint with ability to rotate $\pm 15^{o}$ in range. The inner snake is strung together by one centre cable and that of the outer snake is three cables as shown in Fig. 18. By the combination of rigid and slim modes between the inner and outer snakes, thanks to embedded cables, the robotic system can advance and steer in any direction. A prototype with dimension of 12mm in diameter and 300mm in length was made and tested in porcine model. The results indicated that the HARP system was able to follow a three-dimensional curve and hold its previous configuration.

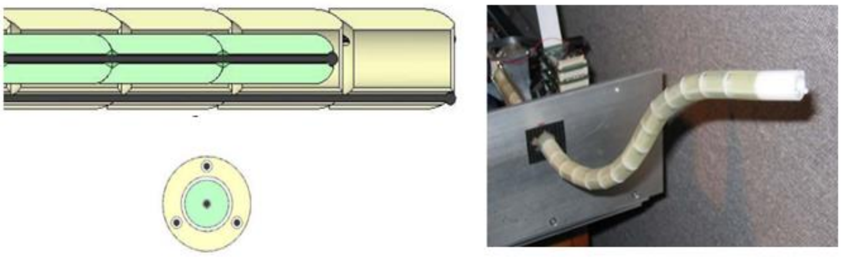


Fig. 18. The HARP prototype and cross section view [16]

Deriving from this design, the researchers in [8, 22, 23] introduce a device intended for transoral surgery namely Medrobotics Flex System. It is made from 50 discrete linkages with the leading one being controlled by the surgeon. Then, the remaining linkages follow the pathway of the leading linkage by the "follow-the-leader" strategy.

Fig. 19. The distal end of flexible tip [8]

A high-resolution camera, light-emitting diodes, and two flexible instruments are attached to the most distal linkage of the endoscope. The flexible instruments like grasper or cauterizing device are inserted and manually controlled by the surgeon. This surgical robotic system was already used for transoral robotic surgery in human body with positive results [50].

Fig. 20. The master and slave transluminal endoscopic robot (MASTER) system [25]

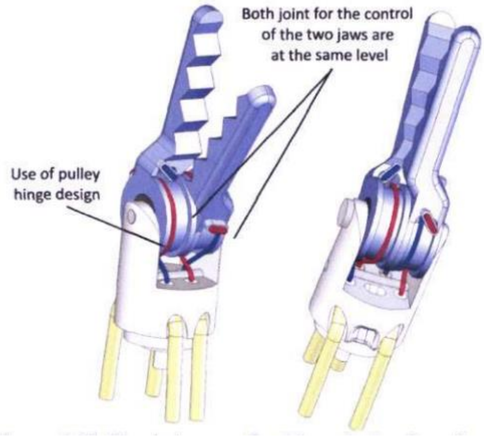


Fig. 21. Pulley hinge design for gripper [26]

The MASTER robot which is given in previous section utilizes TSM as the main mode of transmission. A recent prototype which is commercialized at EndoMaster is shown in Fig. 20. The slave manipulator includes two separate arms; one is an electrocautery hook for cutting and the other (the right arm in Fig. 20) is a grasper for manipulating the flesh of the patient (Fig. 20). The two robotic arms with nine DOFs in total are fixed to the distal end of the endoscope (GIF-2T160, Olympus Medical Systems Corporation, Japan) and driven by tendon-sheath mechanism. At the distal end, the rotational joint is created by attaching the tendons to a pulley (Fig. 21). The MASTER system has been used for endoscopic submucosal dissection (ESD) [51]. The clinical study was conducted on 5 patients with gastric or antrum lesions showing that the median dissention time was 16 min. Apart from some initial success, this systems still need further developments like improving the inserted force, enhancing the haptic feedbacks, and ability for instrument exchange.

Scorpion shaped endoscopic robot (Kyushu University, Japan) consists of two symmetric robotic arms controlled by external traction cables via sheaths and an integrated camera (see Fig. 22). Each robotic arm is capable of moving up, down, right, left, and opening/closing of the tip by five wires totally. The tip of the forceps is 10mm long, 2mm wide and can grab a 6mm-object with the force of more than 3N.

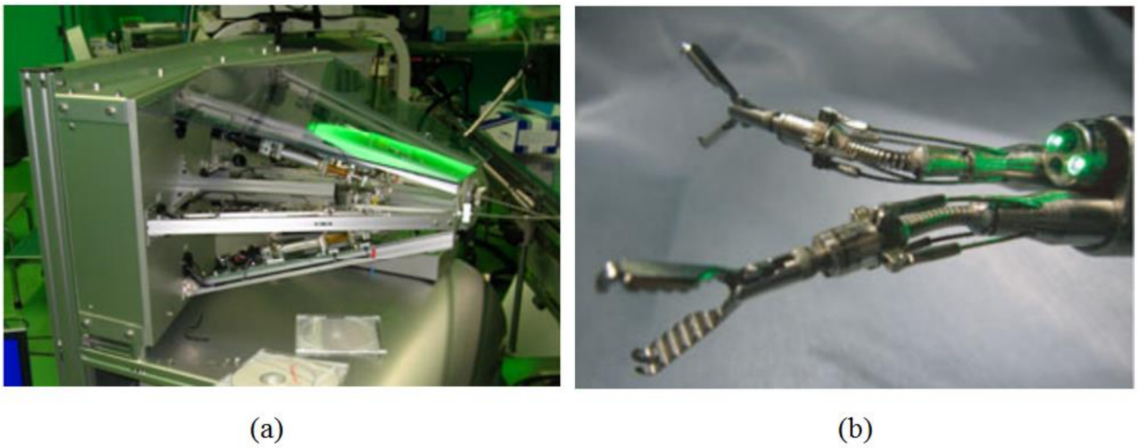

(a) (b)

Fig. 22. Overview of Scorpion shaped robotic system (a) The actuator housing, (b) Scorpion shaped robot [11]

Stepping motors are positioned in a cone shape with the robot's base at the centre to pull all the contraction cables (see Fig. 22). In order to do surgical procedures, two operators are required; one controls the endoscope and one regulates the arms. Although this system seems to be simpler and lighter than MASTER system, no pre-clinical test is carried so far.

The STRAS system (see Fig. 23) is a robotized version of the Anubiscope [52] which was designed by Karl Storz for transluminal operations. The main endoscope (18mm in diameter) provides two flexible instrument channels with the diameter of 4.2mm. It has a 35cm long passive flexible shaft with the distal section being controlled in two orthogonal directions by two pairs of antagonistic cables-routed sheaths. The instruments are designed with the same architecture as the endoscope. They contain a passive flexible shaft of diameter 3.6mm and an articulated distal section. The pair of defection cables is driven by a set of helicoidal, spur gears, and Harmonic Drive servo-actuator. In addition, the closing mechanism of instruments is actuated by another Harmonic Drive servo-actuator through pinion-rack and push-pull cables. With the initial prototype, the robot can be teleoperated by one surgeon. However, the authors have shown that the most difficult part is control problem since the instrument deflection is unpredictable.

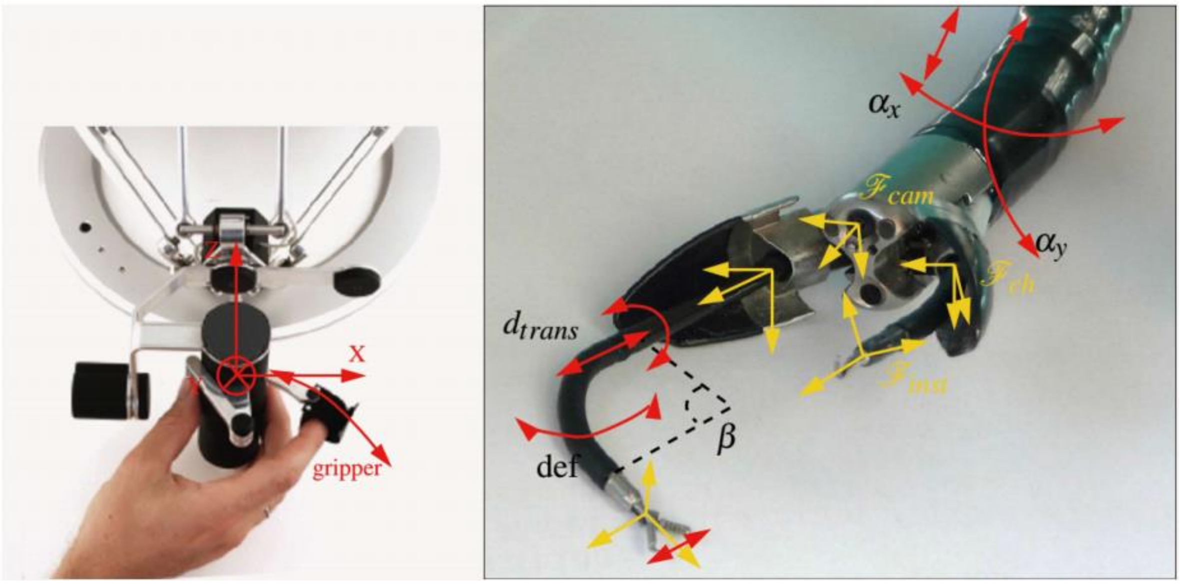


Fig. 23. Master interface and STRAS system [47]

Modelling and control

Modelling and control are much more challenging for the use of cable-driven surgical robots. There are two main approaches for the modelling of the cable-driven surgical robots including discrete and continuous methods. Modelling relates to the characterization of position/force transmission in the cable-driven surgical system. The most famous kinematic framework for conventional rigid-link manipulator is discrete approach, in which the entire robot including of a series of joints and links is described by the homogeneous transformations derived from Denavit-Hartenberg (D-H) parameters. Some of cable-driven surgical robots employ this method to form the kinematic framework [33, 53]. In contrast, constant curvature kinematic framework is the most well-known for continuum robots. In this framework, the curvature, length, and angle form a set of coordinate parameters to represent any position and orientation of operation points in the robot [54, 55]. Apart from these two prominent approaches, there are other methods based on the mechanics frameworks as lumped parameter, energy methods, and elasticity theories [56]. For example, the dynamic governing equation of a model of coupled tendon-driven system is derived from Kim et al. [57] that is then used to estimate the operating force at the end-effector. The authors in [58] used the Lagrangian method to derive the dynamic model of a class of tendon-driven manipulators with the viscoelastic properties of the tendons, the inertias of the pulleys, and the transmission kinematics. Chiang et al. [59] and Phee et al. [60] used analytical method to mathematically model the tendon-sheath and predict the end force and elongation without using the attached sensors. Similar approaches also carried out in the works of Agrawal et al.

and Palli et al. [61-64]. However, these approaches require an exact measurement of the cable configurations in terms of curve angles during the operation. This requirement is impossible for the real surgical system due to the complex procedures to provide the curve angles. In a different approach, Do and his colleagues [65-81] presented a novel dynamic friction model for flexible tendon-sheath that incorporates both the velocity and the acceleration information. To characterize the tendon motion transmission, novel developments of backlash hysteresis models also proposed in these studies. Unlike existing studies on the tendon-sheath mechanism, the new friction model structures consider the whole TSMs as one element instead of using the discontinuous lumped-mass models that are quite complex in real applications with the requirement of multiple sensors and calculations. The new models exactly describe the separate hysteresis curves and the friction lags using new sets of velocity and acceleration dependent functions. In addition, they are able to provide continuous force information with respect to time for both small displacements (the pre-sliding regime) and large displacements (the sliding regime) regardless of the use of configuration information for the model approach as long as the configuration remains constant. With the continuous model approach, only the position/force information at the two ends is required for the identification process that avoids the complex measurement of the cable configurations during the operation.

We can approach the control problems for the cable systems using two separate methods namely feedback and feedforward control. That former one is commonly used in many researches [33, 53, 81-84]. The main advantages of this approach are high accuracy and noise reduction ability. In addition, the disturbances and uncertainties like the change of cable configuration and external force from operation environment are completely eliminated using nonlinear and adaptive control schemes [73, 75-77, 79, 80, 85, 86]. However, it is still complex in terms of construction, calculation, and needs feedback information like position and force that are challenging in surgical robots. From this point of view, the latter one is also applicable. Based on the cable configuration, Do and his co-workers [81] proposed a feedforward control scheme which does not need any complex inverse models and necessary feedbacks. This property is very important for surgical application because of size constraint and sterilization problem that physical sensors cannot be mounted into robotic arms. The experiments showed good tracking performance not only with periodic motions but also with non-harmonic sequence of motion. It is beneficial in surgery since most of surgeon’s motions are non-harmonic.

Advantages and disadvantages

Compared with tendon-routed sheath, the main advantage of tendon-routed pulley is the ability of producing the high force at the distal end. However, taking the design of EndoWirst as an example, the complexity, steel cable fatigue, sterilization issues, and high associated cost are still the challenging problems. Regarding the mechanical perspective, the main limitation is the fatigue resistance of steel cables because of small repeated bending radius over the pulleys, which limits the lifespan of EndoWrist to only ten procedures. According to the engineering standard, the range of pulley-to-cable (D_{pulley}/d_{cable}) ratio should be from 18 to 42. However, this range is only from 6 to 8 for EndoWrist system. Therefore, with the repeatedly small bending radius, the steel cable failure will appear and result in expensive replacement costs [87]. Apart from many undeniable benefits of tendon-sheath abovementioned, there are still some underlying drawbacks as its nonlinear friction, backlash hysteresis, and poor force delivery resulting in the difficulties in modelling as well as control problems [88]. In addition, stiffness enhancements for the surgical tools are also main issues.

System	Diameter (mm)	Length (mm)	DOFs	Actuated by	Bending angle (deg)	Force (N)	Torque (N.mm)	Application

According to recent literature review, compared to other kinds of actuators, cable is most prominent candidate in surgical robots (refer to Table 1 for more details). In addition to lightweight, miniature, and flexibility, cable is very safe when being applied to the human body. On the one hand, it can be made from bio-material like stainless steel. On the other hand, in the worst case of failure as broken cable, the safety still can be guaranteed. In contrast, fluidic flexible actuators which will be given in the next section are operated with high pressure or smart material actuators that need high temperature or voltage. These types of actuators make them still challenges in surgical applications.

B. Fluidic actuator

Hold the same properties as cable actuators, flexible fluidic actuators also can provide high flexibility with the power supply being installed away from the joints. Otherwise, owing to high compliance and bio-compatibility with non-energized parts, they are excellent candidates for various medical applications such as miniaturized surgical manipulators [89-93], catheters [94, 95], graspers [96], positioning system [97], tissue removal tool [98], fluidic actuator for neurosurgical instrument [99], and hydraulic hood for ESD [100]. Based on the review of applications, the dimension of fluidic actuators is also various, ranging from 0.9mm (Catheter [95]) to 35mm (TIFF-FLOP [92]) (see the table 2 for more details). The design concepts, modelling, and control issues as well as their advantages and disadvantages will be reviewed in the subsequent contents.

Table 1: Tendon-driven robots for laparoscopic surgery and NOTES systems

Endowrist [3]	8	_	2	cable	90	_	_	Laparoscopy
Endo-Periscope III [21]	5	_	2	cable	110	_	_	Laparoscopy
Micro-manipulator [19]	2.4		2	cable	90		_	Foetal surgery
DLR MICA instrument [101]	10	20	2	cable	40	10	600	Laparoscopy
Laprotek [102]	10	_	5	cable	180	13	_	Laparoscopy
Dexterous manipulator [103]	10	_	4	cable	180	2		Laparoscopy
Robotic Forceps [104]	10	_	2	cable	90	_		Laparoscopy
Multi-disk Wrist [13]	5	30	2	cable	90	_	250	Laparoscopy
Articulated robotic medical probe [105]	12	12	2	cable	10	_	_	Laparoscopy (Cardiac surgery)
Over-tube [20]	23	120	3	cable	90	15	_	NOTES
STRAS [47]	18	350	10	Cable-conduit	145	8	_	Endoluminal ,Transluminal surgery
HVSPS [106]	10	125	21	cable	180	2.1	170	Single-port, NOTES
Scorpion shaped robot [11]	_	_	4	Cable-conduit	_	3	_	NOTES
MASTER [7] [24]	7	41.7	9	Cable-conduit	90	3	_	NOTES
ViaCath [9]	4.75	900	6	Cable-conduit	_	0.5	_	NOTES
USGI Cobra [10]	18	1100	_	cable	_	_	_	NOTES
R-Scope [10]	14.3	1030	_	cable	_	_	_	NOTES

Conceptual design

Flexible fluidic actuators usually consist of flexible structures which can be deformed under the applied pressure from fluidic (i.e. pneumatic or hydraulic) actuation. Fluidic actuators can be divided into three main types namely elastic fluidic, piston-cylinder fluidic, and drag-based fluidic actuator. Being most popular compared to the remaining two fields like MEMS and flexible medical instruments, elastic actuators comprise membranes or elastic components that can elastically expand under applied pressure [89, 90]. Therefore, in this study, only kind of this actuator will be discussed. Based on studies in [90], flexible fluidic actuators are categorised into two major groups that are bending due to internal chambers differently pressurized and anisotropic rigidity. Most of devices in the former group contain an elongated shape closed at one end and hindered radial deformation. When a chamber is pressured, its length increase while that of others is unchanged, making the whole device bending. In contrast, the tools in the latter category provide an elongated shape closed at one end and a rigid area that is stiffer than that of the rest. After being pressured, the length of stiffer area grows less than the rest, leading the desired bending motion. The details of design and working principle will be presented in the next sections. Fluidic actuators have been used in many applications. However, this review only focuses on the use of fluidic actuators in surgical applications. Detailed descriptions will be given in next sections.

Surgical devices with bending due to different pressure from internal chambers

An electro-pneumatically or electro-hydraulically driven flexible micro-actuator (FMA) is introduced in [107, 108]. This actuator has total three DOFs (pitch, yaw, and stretch) with the diameter ranging from 1mm to 20mm. It is made of fibre-reinforced rubber and shaped in cylinder with three internal chambers (see Fig. 24). The pressures inside internal chambers are independently controlled by external pressurized sources via flexible tubes and valves. The fibres are embedded inside the rubber in the circular direction with a purpose of preventing the actuator from deformation in the radial direction. The actuators will be bended in desired directions due to different or unequal pressures in the three chambers. For example, if the chamber 1 is pressurized, the actuator will bend in the y direction (see Fig. 25).

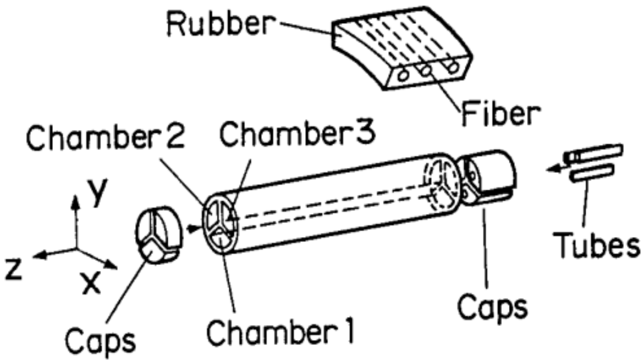


Fig. 24. FMA's structure [107]

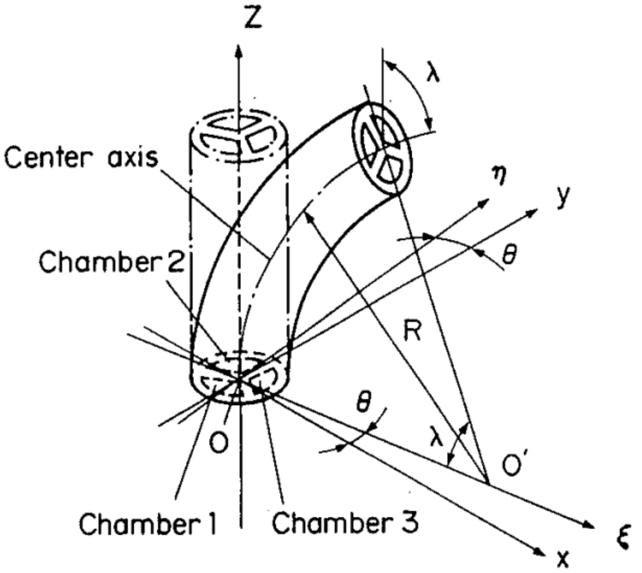


Fig. 25. Bending and stretching based on the supplied pressure [107]

One of the major disadvantages of FMA is the fabrication process due to embedded fibres. In order to improve the FMA performances, some fibres-less designs were proposed. Suzumori et al. [109] added two restraint beams in each chamber to create anisotropic elasticity and make it compatible with stereo-lithography using an unique material while the authors in [110] take advantage of finite-element-method (FEM) to minimize the radial deformation with suitable shape. In different approaches, McKibben actuators were invented in the 1950s by J.L. McKibben and Gaylord [111]. Thanks to the presence of large stroke, high force, and compliance, it has been used throughout in humanoid robotics, human-machine interfaces, prostheses, and medical instruments [91]. The basic structure of McKibben actuators includes a woven reinforced elastic tube as shown in Fig. 26(a). The working principle is briefly described in Fig. 26(b). Due to the constraint of woven, the length of actuator is shortened after being pressured.

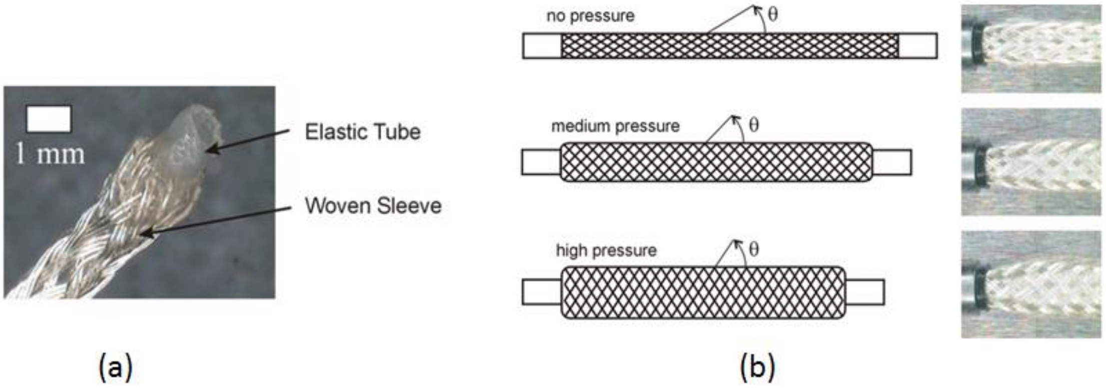


Fig. 26. Miniature McKibben actuators (a) Structure of McKibben actuators, (b) The working principle of actuators [91]

These well-known actuators are scaled down to a diameter of 1.5mm and a length of 22mm and they still provide the high force densities [91]. To incorporate these dedicated fluidic actuators, Moers and his colleges [112] presented a surgical instrument with three fluidic actuators, spacer disks, and an elastic tube (see Fig. 27). To control this system, the high pressure hydraulic valves are miniaturized and incorporated with the actuators in its module. The experimental result shows that the actuator can bend up to 55^0 at the pressure of 10 bars.

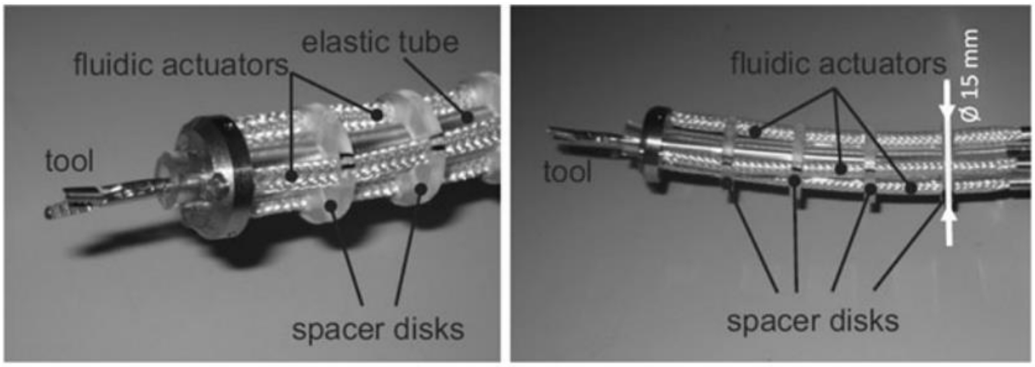
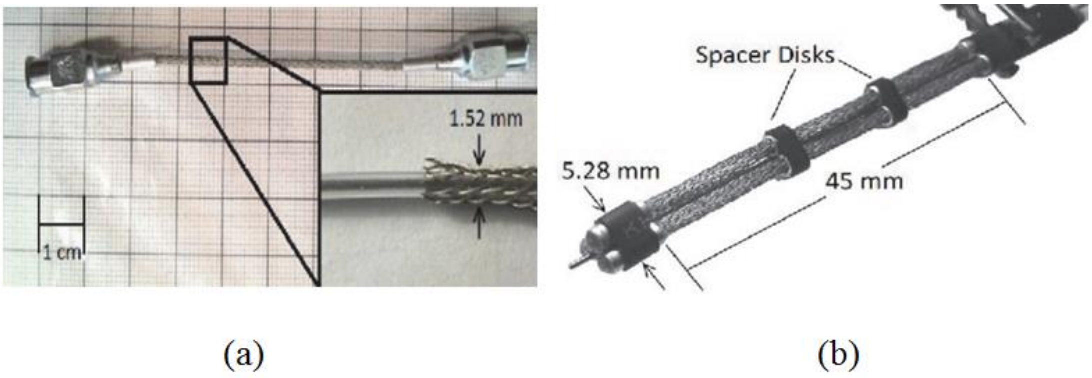


Fig. 27. Surgical instrument with miniature McKibben actuators [112]

To increase the dexterity and reachability of neuro-endoscopic instruments in performing complex intraventricular procedures, Eastwood et al. [99] used miniaturized McKibben actuators made from high purity silicone rubber tubing (0.94 mm in outer diameter) and silver plated braid mesh to create ten contractile actuators with outer diameter of 1.52 ± 0.029mm (see Fig. 28(a)). The three McKibben actuators are combined to form a bending segment with a diameter of 5.28mm and a length of 45mm (see Fig. 28(b)). Initial tests showed that ten individual McKibben actuators can provide contractile force of 4.83 ± 0.38N and the bending angle of segment meets the required range of motion for neurosurgery up to 70^0. The authors also proposed some modifications to scale the individual actuator to 1mm in outer diameter but able to maintain the bending ability. However, no experiments are carried out so far.



(a) (b)

Fig.28. Neuro-endoscopic instruments (a) Single actuator (b) Assembled McKibben bending segment [99].

Based on the same principle of being pressurized unequally, the researchers in [92, 113] developed a bio-inspired surgical manipulator namely STIFF-FLOP which is capable of omnidirectional bending, elongating, and changing the arm stiffness. In the STIFF-PLOP design, an elastic cylinder is made of silicon that is soft and suited for three internally embedded chambers as given in Fig. 29.

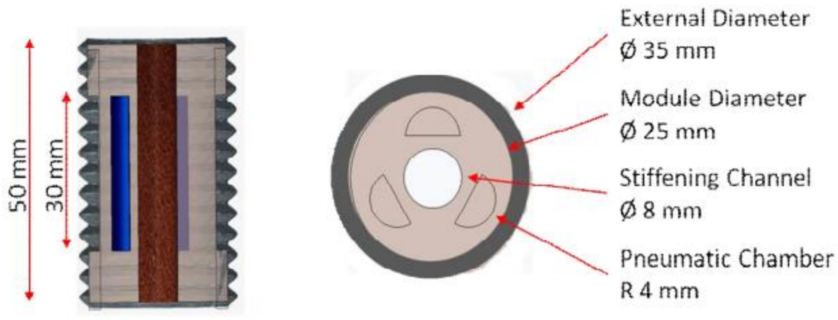


Fig. 29. Cross section design of STIFF-FLOP [92]

The three chambers in STIFF-FLOP system are arranged equally in radial direction and act as fluidic actuators that are characterized in the previous sections. There is one central channel as granular jamming material container. The stiffness of this manipulator can be adjusted by controlling the applied vacuum. In order to minimize the inflation in radial direction while maximizing the bending angle, a braided structure is used outside the module. Two modules are fabricated and connected for validation as discussed in [113]. The results demonstrate that the designed manipulator can bend up to 260^0, elongate up to 62%, and able to change the stiffness with more than 66%.

A pair of flexible fluidic actuators for medical catheter are presented in [96]. Each of them has a fixed base made of rubber and two long and narrow tubes that are maintained to be parallel by a core (see Fig. 30(a)). There are pump units setting on the partition wall, which will transfer fluid between the two channels to achieve bending movement (see Fig. 30(b)). Some other patterns and systems which possess similar design concepts are also introduced in [114-116].

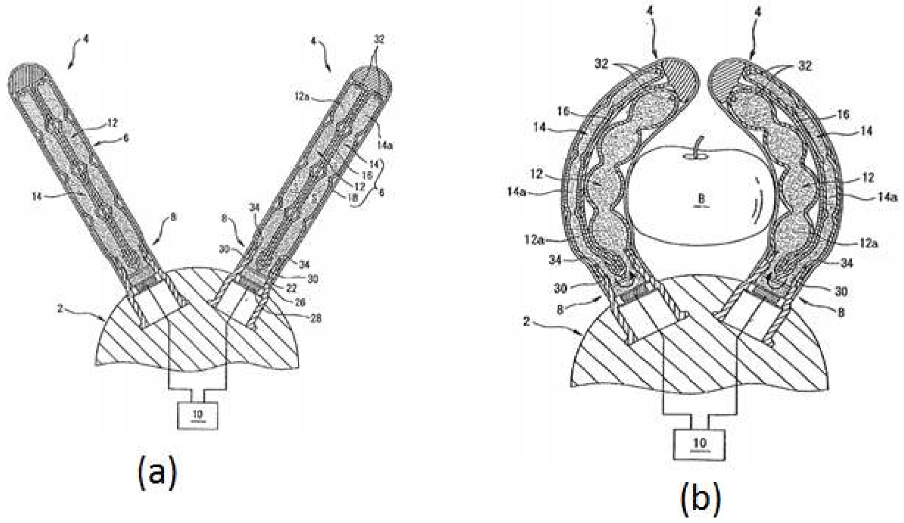


Fig. 30. Flexible fluidic actuators for medical catheter (a) The mechanism of actuator, (b) Bending movement [96]

Those above determined actuators reply on the difference of applied pressure. Apart from it, there is another method to activate flexible fluidic actuators called anisotropic rigidity. Fundamentally, the devices are constructed from expandable materials that possess higher rigidity compared to the other areas in the body. Due to the applied pressure, the length of lower rigid areas will be enlarged more than that of higher areas followed by the bending.

Surgical devices with bending due to anisotropic rigidity

A pneumatic balloon actuator (PBA) was developed in [117]. Being shaped like a cantilever, it consists of two thin and flexible films, upper silicon rubber membrane and lower polyimide film glued together (see Fig. 31(a)).

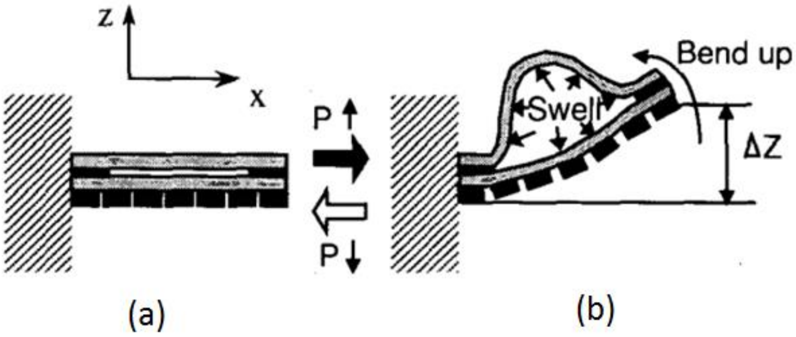


Fig. 31. Cantilever-shaped PBA (a) Structure and (b) Working principle of PBA [117].

Internal cavity is formed by surrounding sealed edge with silicone rubber glue. Thanks to difference in the rigidity between the two layers, the structure is able to have both out-of-plane in the z direction and horizontal displacements (see Fig. 31(b)). The internal chamber is swollen by the pressure and the upper membrane significantly inflates without using any bending support. Due to the moment of tensile force from the inflated membrane, the lower film is also bended and leads to the bending achievement. There is a series of rubber ribs glued in the film to prevent unwanted swelling of the film and undesirable corner of folding [117].

Chang et al. [118] utilized the same theory to come up with the design of a millimetre-scale actuator that composes a deformable silicone material with sub-millimetre scale parallel channels and bonded with a thinner and stiffer material (Fig. 32).

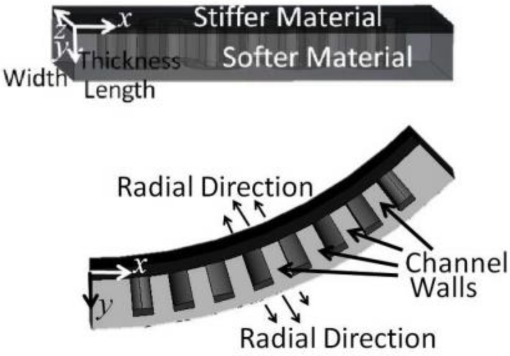


Fig.32. Overview and bending shape of actuator [118]

The introduction of inside parallel channels will hinder the expansion in thickness direction and enable bending at low working pressure. In [119], the authors integrated three of these bending actuators to create a spatial bending actuator (see Fig. 33). The experiments were carried out to demonstrate that the actuator can provide 360^0 bending and a torque of 26.39 mNm. Similar approach was also applied to surgical systems as studies in [120-123].

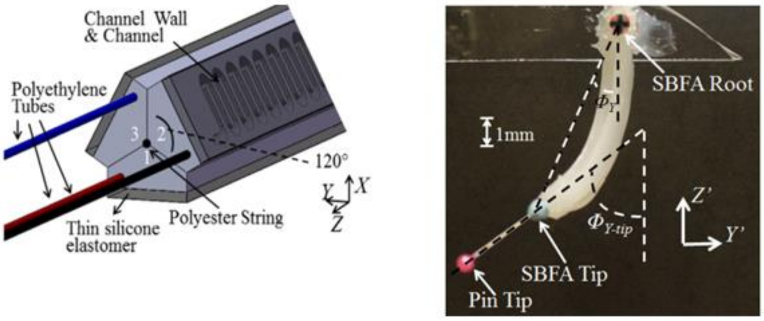


Fig. 33. Assembled actuator and bending posture [119]

Balloons are also widely used in flexible fluidic actuators [89, 90]. A hydraulically-driven flexible manipulator was developed for neurosurgery as discussed in [124].

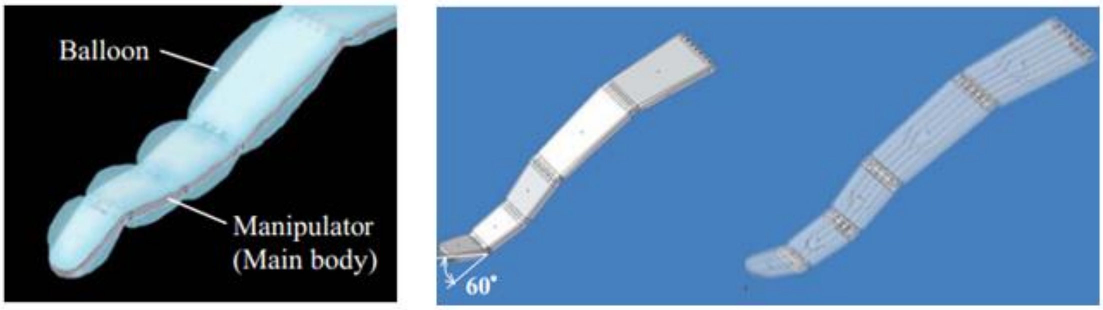


Fig. 34. The design of flexible manipulator [124]

It can be seen from Fig. 34 that the main body of flexible manipulator is the articulated joints and links with flat surfaces for neurosurgery. The balloons which are put in both up and down sides of links are driven by the physiological saline flows via a hole of 0.5 mm diameter in the centre of the surface. One interesting feature of this manipulator is that instead of being bendable by itself it can be positioned inside the brain by unequally inflating the appropriate balloons, leading to the bend in opposite direction once the balloons touch the delicate brain tissues. Experiments were successfully conducted in anaesthetic pig to validate the movement and the measurement of applied pressure with un-harmful leakage thanks to physiological water.

A system used to fix and orientate the catheter tip was also proposed in [97]. Three micro and inflatable balloons are mounted on the tip's side and controlled by electro-thermo-pneumatic micro-valves. After being deflated, these balloons will press and exert forces on the vessel's wall. As a result, the catheter tip will be deformed and its position and orientation can be easily obtained (see Fig. 35).

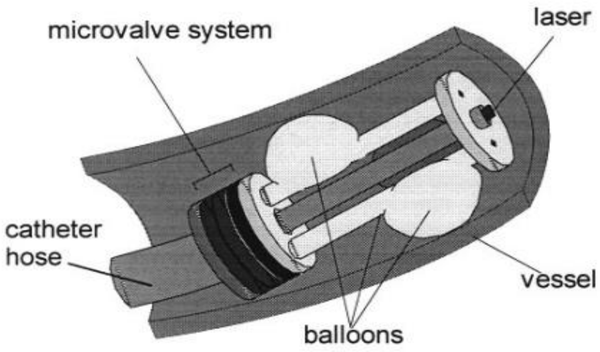


Fig. 35. The catheter tip inside the blood vessel [97]

In order to effectively carry out endoscopic submucosal dissection (ESD) for early stage cancer treatment in the digestive tract, Matsuo et al. [100] developed a hood with hydraulically variable tip diameter as shown in Fig. 36. The tips and the base are made of acrylic resin using 3D printing technology. The tip parts and the base are connected by joint sheet and traction sheet. There is one embedded silicone tube which plays a role as hydraulic actuator inside the base. When water is injected into this tube by medical syringe, it will inflate and makes the traction sheets deformed and the tip part opened. The prototype with the tip diameter of the hood ranged from 9.8mm to 17.8mm was fabricated and attached to the tip of a flexible endoscope. The ESD procedure was successfully carried out in a porcine stomach and the results demonstrated that the hood is able to generate enough force (1005 mN) to lift up the lesion and expand the view of submucosa.

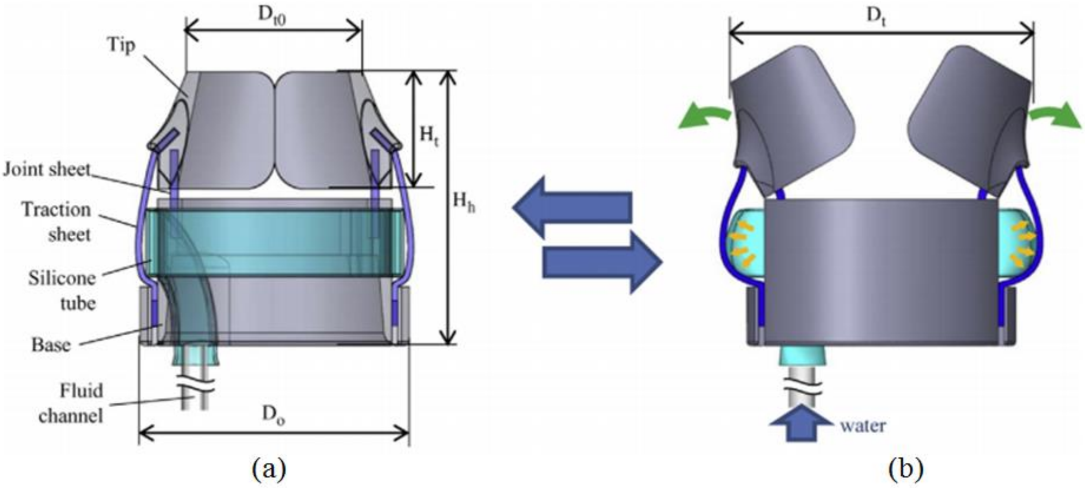


Fig. 36. Design of hood with hydraulically driven variable tip [100]

One of the state-of-the-art for surgical tools using fluidic actuation is the tissue removal device designed by Vasilyev et al. [98] from Harvard Medical School, USA. This tool is attached and intergraded to a steerable concentric tube robot that can be inserted into the beating heart via peripheral vessels. The tool design consists of two parts (a stator and rotor) with the sharp leading edges to grab and slice the tissue layers, which are bonded by an embedded bearing as shown in Fig. 37. The rotor is soldered to an inner rotating tube while the stator attaches to a fixed outer tube. The aspiration of cutting debris is produced by a vacuum pump. A prototype with the diameter of 2.1 mm is fabricated and successfully experimented *in vivo* and *ex vivo* with porcine models.

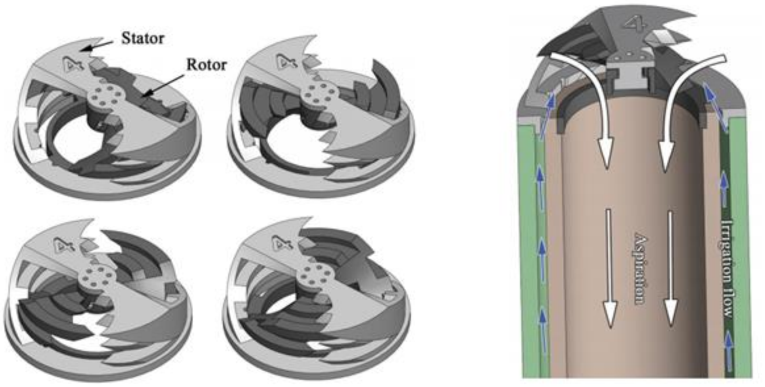


Fig. 37. The tool design and illustration of fluid flow [98]

Modelling and control

The modelling and control problems of flexible fluidic actuators as well as soft robotics have been extensively reviewed in recent studies [125-127]. Those robots with entire flexible body and powered by fluids have been not fully understood in terms of modelling, dynamics, and control since the deformation of the actuator configuration is continuous, varyied, complicated, and highly compliant [125]. Piece-wise constant curvature (PCC) is one of the most well-known models to deal with these robots. With the assumption of PCC that each segment in multi-segment arm has constant deformation, the kinematics can be decomposed into two mappings namely robot-independent and robot-specific mappings [127]. The former is obtained from joint or actuator space (fluidic tubes or applied pressure) to configuration space that characterizes constant-curvature arcs. The latter is applied to map the space configuration into task space which describes the position and orientation along the backbone of the robotic arm. The mapping from actuator to configuration space is robot-dependent because various actuators will impact arc parameters in different ways. In contrast, the mapping from arc parameters to the pose along the backbone is simplified as kinematic mapping and robot-independent due to piecewise constant-curvature assumption. Regarding the robot-specific mapping, some typical methods have been applied. For example, Webster et al. [128] utilized Bernoulli-Euler beam mechanics to predict the deformation of flexible robots. Onal et al. [129] derived a static analytical model under some advanced conditions. In order to derive the transformation matrix between the configuration space and task space, authors in [127] also stated that many methods can be applied with the same results such as Denavit-Hartenburg approach, Frenet-Serret frames, and exponential coordinates. However, the main limitation in PCC assumption is the assumption of constant curvature of each segment. In practice, the curvatures are always varied from time to time during the robot operation. Mahl et al. [130] also developed a new model for non-constant deformation robots.

Based on the constant curvature theory, the main idea of this method was to subdivide each single section into some virtual units and then applying constant curvature approach for each of these sections. However, Andrew and his colleague [129] demonstrated that the PCC model is only applicable for soft fluidic elastomer manipulator.

Most of fluid-powered flexible robots employ the model-free open-loop control approach. This means that the proposed methods only control the valve with the time duration of turning on or off depending on the different tasks rather than based on the dynamic model. This simple method has widely applied to diversified soft-robotic systems [125, 131]. However, the dynamics of flexible robots is absolutely vital for control problems followed by new robotic capabilities. In [131], researchers constructed a dynamic model for fluidic manipulator made of pure soft elastomers. They also applied new methods that can identify unknown parameters and planning optimization algorithm with the constraints of gravity, compliances, and actuation limitations. Dynamic models of hard or semi-soft robots [132, 133] were also considered as a technique for flexible robots. An overview of current surgical applications using fluidic actuators is given in Table 2.

Advantages and disadvantages

The advantages and disadvantages of flexible fluidic actuators were partially discussed in the literature [90]. With respect to the human safety, fluidic actuators made of biocompatible materials have no energized parts that opposite to electricity related or Shape Memory Alloys and thermal actuators. They can handle the tissue without any impairment due to their compliant property. Compared to the traditional mechanisms, flexible fluidic actuators are easy to change its shapes since they are conducive to enter and retract from the human body as well as are able to operate in confined spaces of the human GI tract. In addition, flexible fluidic actuators possess abilities to provide high force at small size, especially at microscale. In a recent study, fluidic actuators deliver among the highest force and power densities compared to other type of actuators [89]. With these promising properties, ever the last few decades, numerous micro-hydraulic and micro-pneumatic actuators have been applied in some surgical applications. However, their main limitations are the bulky, complex, and high power supply requirements. Safety is also the main challenge. From the surgical points, these heavy systems can be installed outside the human body, which does not have negative effect on the surgical quality. The key challenge can be identified as the difficulties in model and control problems due to nonlinear friction and backlash hysteresis. Since the properties of flexible materials are considerably different from the conventional and rigid ones, most of current approaches are not able to provide accurate models and efficient controllers. This significantly degrades the system performances. Another drawback of fluidic actuators is the need of high pressure in the operation process. If this high pressure is not efficiently controlled, the human safety is put in danger.

Table 2: Characteristics of flexible fluidic actuators-driven surgical systems

System	Diameter (mm)	Length (mm)	DOFs	Actuated by	Bending Angle (deg)	Force (N)	Torque (N.mm)	Pressure (Bar)	Applications

FMA [107, 134]	4	12	3	Fluids	95	0.15	-	4	MIS
Catheter [97]	5	4	2	Fluids	5	-	-	0.1-0.2	MIS
Catheter [94]	4.9	20	3	Fluids	35	-	-	10	MIS
TIFF-FLOP [92]	35	50	3	Fluids	120	41.4	-	0.65	MIS
miniature McKibben[91]	1.5	22-62	3	Fluids	-	6	-	10	MIS
SBFA [119]	9.6	78.4	3	Fluids	125	-	26.39	1.3	MIS
Bi-bellows [120]	10	120	1	pneumatic	180	-	-	1.25	MIS
PBA [135]	6	-	1	pneumatic	-	1.2	-	0.8	MIS
Catheter [95]	0.9	5.5	1	Hydraulic	160	-	-	0.8	MIS
Hydraulic forceps [122]	-	-	1	Hydraulic	-	< 1	-	-	MIS
Balloon actuator [117]	16	16	2	pneumatic	90	-	-	0.6	MIS
Variable tip hood [100]	9.8-17.8	-	1	Hydraulic	-	1.005	-	3	ESD

C. Smart Material Actuators

Smart materials such as shape memory alloys (SMAs) and piezoelectric actuators will be investigated in this review in terms of property, design, modelling, and control. SMAs belong to the group of shape memory materials (SMMs) which can memorise and recover to their previous forms under the change of temperature or magnetic stimulus. This phenomenon is known as shape memory effect (SME). Because of high work density, large force and displacement, bio and magnetic compatibility, numerous surgical robotic systems have exploited SMAs as the main mode of actuation such as robotic catheter (Tohoky University and University of Hyogo-Japan [136, 137]), endoscopes (Tohoky University-Japan and Université Pierre et Marie Curie-France [138, 139]), surgical graspers (Sharif Univesity of Technology-Japan and BeiHang University-China [140, 141]), capsule endoscopes (Carnegie Mellon University-USA [142]), and Neurosurgical Robot and Steerable Cannula (University of Maryland-USA [143-145]). By comparison, piezoelectric materials that are used to build ultrasonic actuators can induce the movement under certain voltage. As opposed to electronic actuators, ultrasonic actuators from smart materials offer higher power density, higher torque for lower speed, and precise motions. As a result, they are selected as the actuation means for surgical applications like surgical tools [146] and endoscopes [147, 148].

Basically, SMAs exist in two phases namely martensite at low temperature and austenite at high temperature. By selecting suitable training, heating, and cooling methods, the transformation between the two phases can be achieved. For more details, further reading in some studies [149-151] is needed. In some applications, the most method of actuation is to use external force to deform the robotic structures and then force these structures to recover or contract to their original shapes using internal or external heating sources or magnetic field. Because of instability, impracticability, and poor thermal-mechanic performance of Fe-Mn-Si, Cu-Zn-Al, and Cu-Al-Ni materials, Ni-Ti based SMAs is much popular for practical applications [149]. SMAs have been widely applied for numerous fields such as industrial applications, automotive, aerospace, MEMs devices, robotics, and medical devices [149, 152-155].

Surgical devices

Various surgical devices have been used smart materials as the main mode of transmission. For example, robotic catheters and endoscopes are actuated by the SMA cables that are fixed around the main structure and can pull in order to bend the instruments in different directions [136, 138, 139, 156, 157]. An active catheter as shown in Fig. 38 with bending, torsional, extending, and stiffness controlling abilities was introduced in [136]. The bending mechanism is depicted in Fig. 39. Three SMA coils are placed axially between the inner tube and stainless coil (See Fig. 39(a)). When being heated over the certain temperature, the SMA wires will contract making the joint bent. The electrical circuit with the common ground and the connections of lead wires, linear, and SMA coils are respectively shown in the Fig. 39(b) and Fig. 39(c).

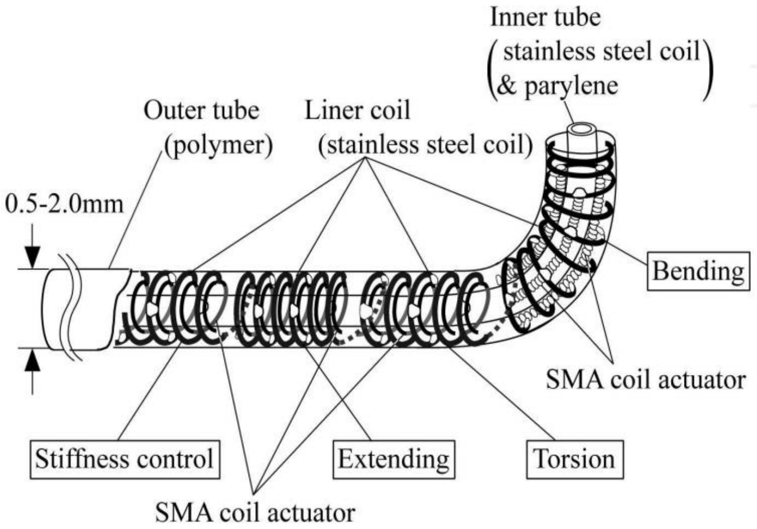


Fig. 38. The overall structure of active catheter [136]

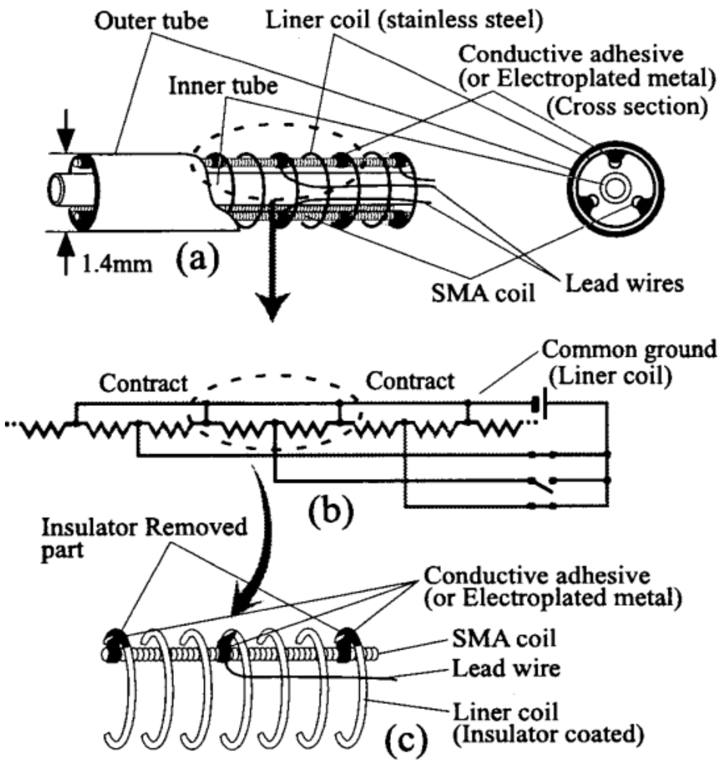
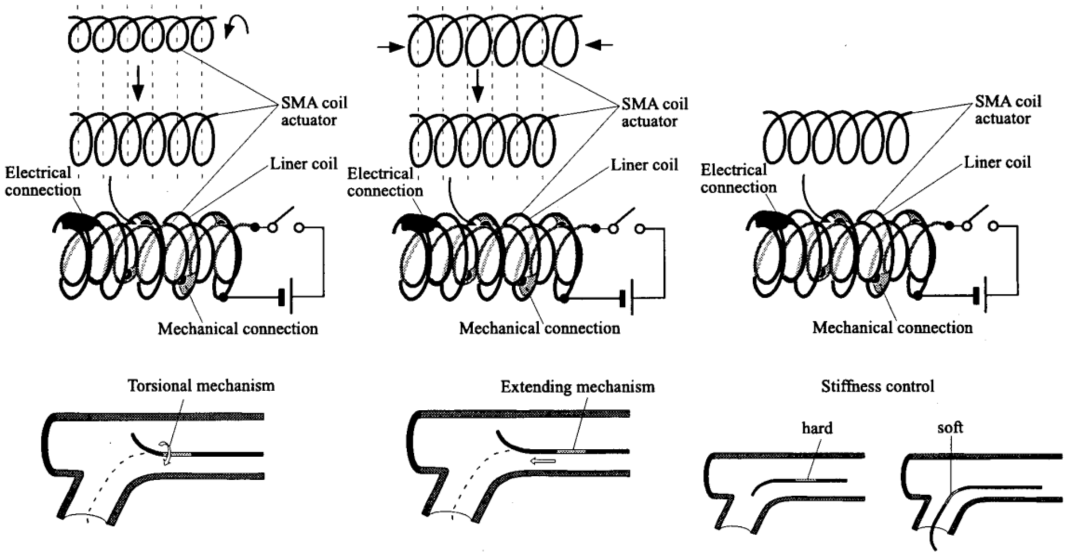


Fig. 39. The bending mechanism [136]



(a) Torsional mechanism (b) Extending mechanism (c) Stiffness control mechanism

Fig. 40. The torsional, extending and stiffness controlling mechanism [136]

The torsional, extending, and stiffness for controlling this catheter is given in Fig. 40. To provide the torsional force, a twisted SMA coil is put inside the linear coil which plays a role as lead wire (see Fig. 40(a)). The SMA coil and catheter will be twisted when a suitable current is applied to the system. Regarding extending mechanism, it is made of one linear coil and one compressed SMA coil and they are co-axially integrated inside the linear coil. If the SMA is heated over a certain temperature by the electrical current, it will extend and create desired elongation for the catheter accordingly. To form the stiffness control mechanism, a SMA coil at natural state is inserted co-axially into the catheter with a linear coil (see Fig. 40(c)). Normally, after a current is applied, SMA will return into initial state, creating translation or bending for the system. However, for this special mechanism, if the current is applied, the SMA coil will be harden rather than deformed. The catheter is fabricated using electroplating with the outer diameter of 1.4 mm where the wall thickness is around 0.1mm. The experiments show that under the current of 80 mA, the torsional angle will be 70^0.

In another approach, the authors in [139, 158, 159] made use of plate springs (tubular SMA actuators) to actively control the bending of flexible endoscopes and catheters. For example, Sars et al. [139] employed a series of paired tubular NiTi-SMAs as local actuators to construct a bending mechanism with very complex 3D configuration (see Fig. 41). They also proposed three distinct methods to integrate plate springs into structure as illustrate in Fig. 42. To find the best parameters for actuator shape, a genetic algorithm-based method namely Steady Method is used. The experimental results indicated that the maximum rotational angle at the unloaded prototype is 10.5^0 and the torque is measured is 17 mNm.

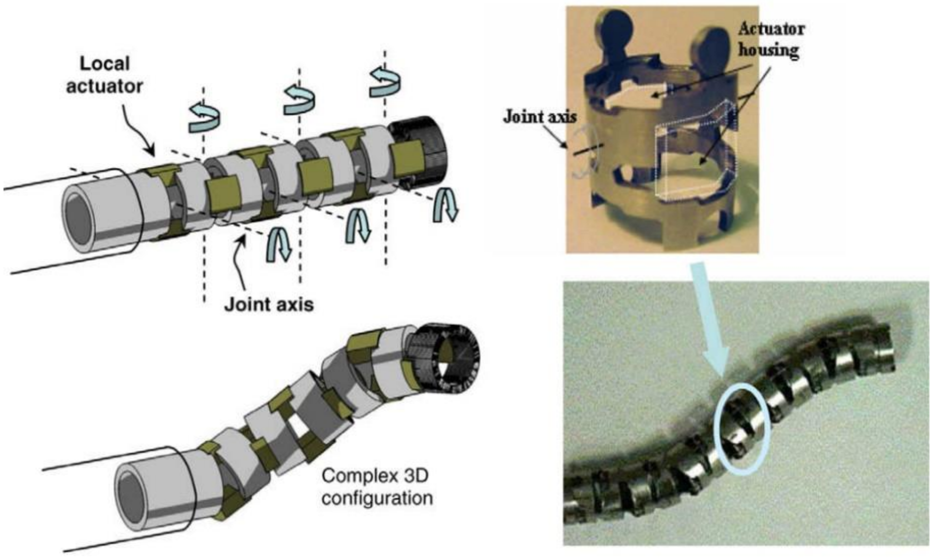


Fig. 41. The mechanical structure of endoscope [139]

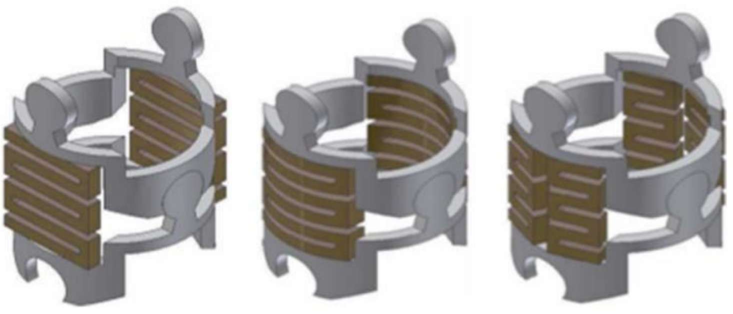


Fig. 42. The integration of plate springs [139]

SMA actuators have been applied broadly to design the grippers for MIS instruments [141, 153, 160-163]. SMA can be used as cable actuator where the contraction force is controlled by the temperature instead of using pulling force from DC actuators. To open and close the grippers, the translation motion of SMA cables are converted to rotation. Based on the layout of SMA wires on the grippers, Damien et al. [160] proposed some configurations for grippers such as parallel SMA gripper, gripper with twist, net SMA gripper, and spiral SMA gripper that can be seen in Figs. 43 (a), (b), (c), (d) respectively.

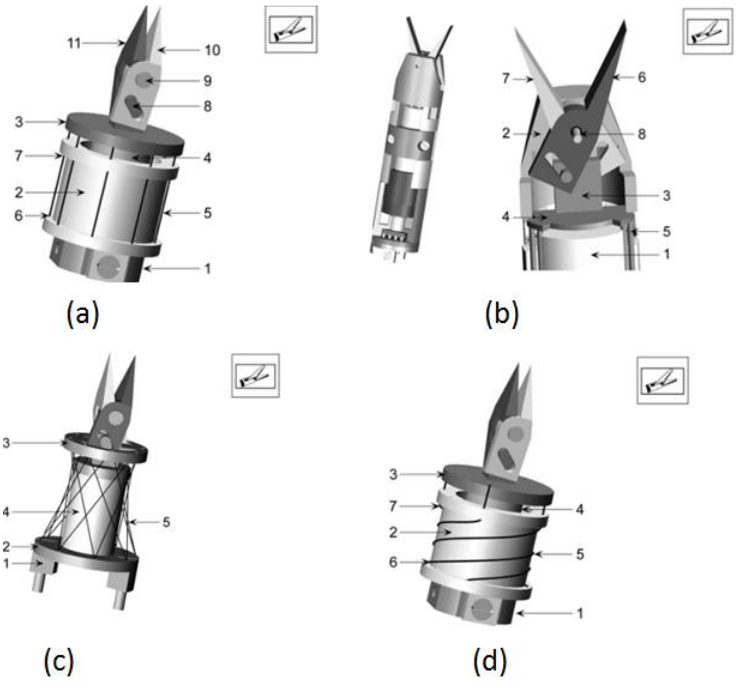


Fig. 43. The different configurations for grippers [160]

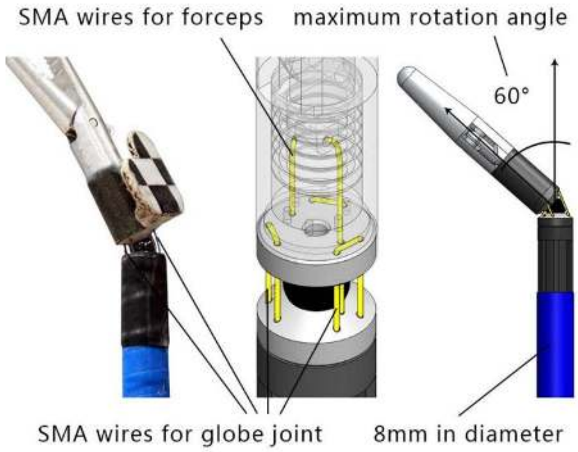


Fig. 44. The SMA driven global joint [141]

A SMA-actuated single-port laparoscopic surgical robot was also developed [141]. To design the SMA actuator, the confrontational double wire configurations which can generate the force at both ends are utilized. The global joint is driven by three pairs of SMA wires that are distributed in the washer's circumferential plane and go through it (see Fig. 44). By heating the SMA wires above a certain temperature, the joint is able to rotate about its axes. This approach was also applied to surgical forceps where another pair of SMA cables was used to generate the clamping force (see Fig. 45). In vivo experiment, the wrist can provide angular motion up to 60^0 and the closing force is 16 N where a voltage of 9.5V is applied.

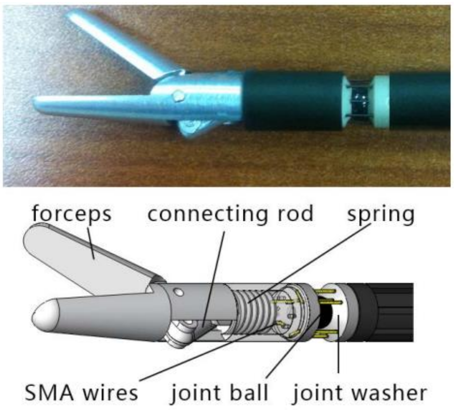


Fig. 45. The SMA driven forceps [141]

Ayvali et al. [144, 145] from the University of Maryland, USA developed a discrete actuated steerable cannula for both diagnostic and therapeutic procedures. In this design, a SMA of 0.53mm in diameter is annealed to get a desired angle at a specific location along the cannula under certain thermal actuation. For each DOF, two antagonistic SMA cables are used to generate the bending forces (see Fig. 46). The copper tube consists of three straight sections with an inner and outer diameter of 1.651mm and 3.175mm, respectively. For the electrical insulation of SMA cables, the high temperature enamel (Rust-Oleum, 260◦C) is coated outside the copper segment which is also covered with a non-conductive rubber for heating isolation. The current prototype can provide up to $\pm 21^0$ for bending angle and about 2N in terms of force.

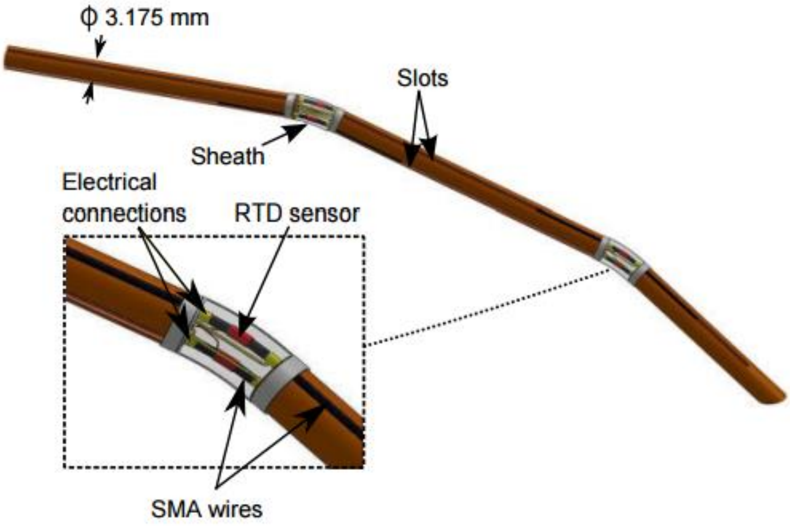
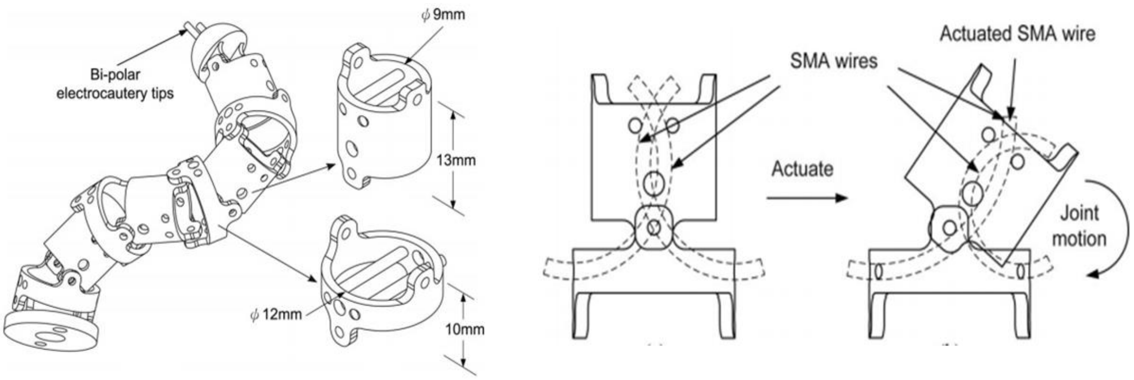


Fig.46. The design of discretely actuated cannula with SMA cable layout [144]

In the same laboratory, the researchers also designed a minimally invasive neurosurgical intracranial robot (MINIR) using SMA wires as actuators [143]. The prototype of robot has nine revolute joints actuated by 0.5mm diameter SMA wires (see Fig. 47). The two adjacent joints are shown in Fig. 47(a). Larger holes are milled for the passage of the SMA wires while smaller holes are designed for the columns. The SMA actuators push against these columns and transmit the force to actuate the revolute joints. Fig. 47(b) shows the working principle of their proposed SMA actuators. Two antagonistic SMA wires are used for each joint so that each joint is able to move backward and forward directions. In stationary state, these two SMA wires play a role of keeping the links to be straight. To rotate the joint in clockwise direction, the left SMA wire will be actuated to reform to its original shape. One-DOF link was fabricated and tested. The results indicated that the average maximum bending displacement was achieved up to $\pm 30^0$ and the maximum force at the distal end was 1.5N.



(a) (b)

Fig.47. Minimally invasive neurosurgical intracranial robot (a) The brass MINIR design, (b) The actuation mechanism

The wireless capsule endoscopy which is a state-of-the-art technology can replace the traditional endoscopy. Capsule endoscopy is usually shaped in pill form with a camera, a coin battery, and a data transfer. Since the passive capsule has many disadvantages such as uncontrollability and the risk of retention, the development of actively controlled capsules with locomotion systems is needed [164]. SMA is prominently exploited to design actuators for these active locomotion mechanisms as well as biopsy application [142, 164-167]. A stopping mechanism actuated by SMA coil and the locomotion inspired by the inch-worm's locomotion principles was designed for a capsule endoscopic robot [142]. The authors made use of dry and wet elastomer (PDMS) micro-patterned adhesives inspired by beetles to stick to GI tract after being pushed by SMA actuated mechanism (see Fig. 48).

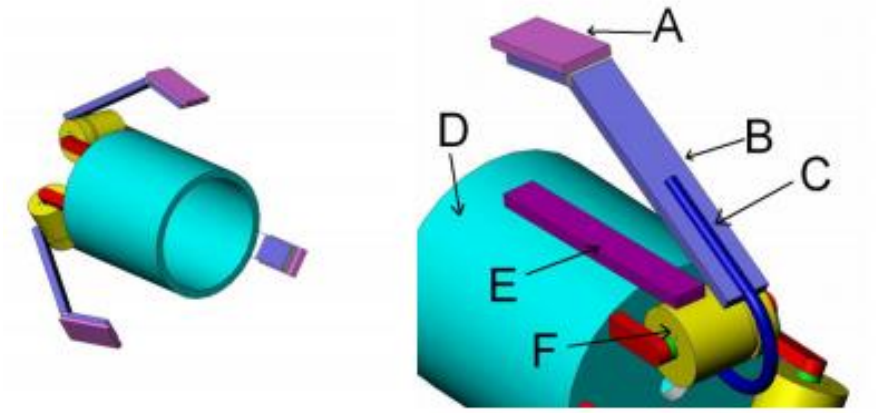


Fig. 48. The design of stopping mechanism, A: Adhesive Pad, B: Leg, C: SMA wire, D: Casing, E: PDMS Spring, F: Pulley [142].

As described in Fig. 48, after being heated by the current, the SMA wire pulls the capsule legs and creates a suitable torque that causes the pulley to turn and rotate the legs. As a result, the rubber spring connected to the pulley is stretched and creates another torque in the other direction. When the torqued induced by the rubber spring is equivalent with the torque created by the SMA spring, the leg stops opening. The rubber spring will pull the leg back if the current is shut off. Regarding the locomotion structure, one more SMA wire is integrated to connect the two casings in the ends. With the pair of SMA and spring working in antagonist style, they can accomplish pulling and pushing tasks forming the locomotion mechanism like inch-worm (see Fig. 49).

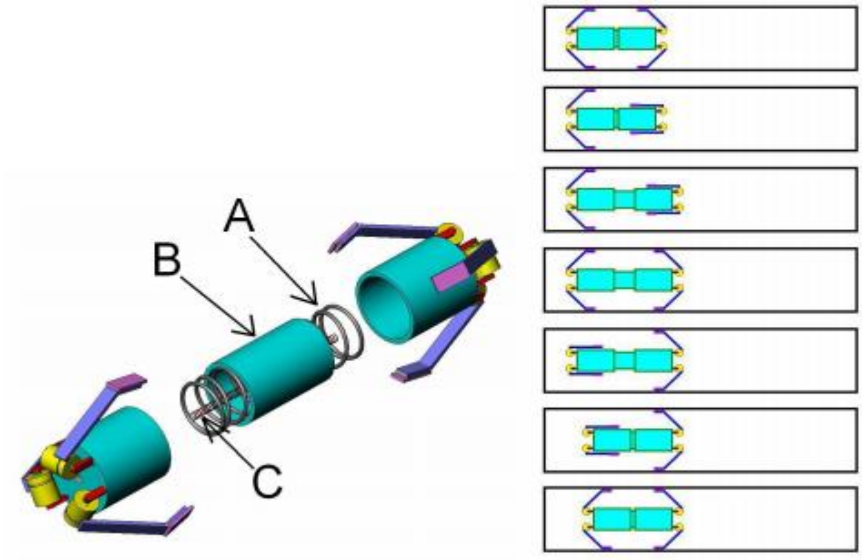


Fig. 49. The structure and the locomotion principle of capsule [142]

Smart materials are also used in ultrasonic actuators. Takemura et al. [168] designed a frictionally driven multi-DOF ultrasonic actuator. It consists of a bar-shaped stator or vibrator and a stainless steel spherical rotor as illustrated in Fig. 50. The actuated joint can be rotated about three perpendicular axes by the combination of three different vibration modes (one longitudinal and two bending modes). The bar-shaped stator is constructed from head, rings, shaft, and stacked piezoelectric rings which are made of ceramic and used to excite both vibration modes of the bar-shaped stator. The geometrical dimensions, shape of stator, and the natural frequencies are calculated by applying the finite element method.

Smart material (SMA and piezoelectric) actuators have been reviewed in terms of design concepts with varied shapes as cable, spring, plate, tube, and ring. For more details, Table 3 is strongly recommended to readers. In the next sections, the modelling, control, and characteristics for the smart actuators will be investigated and explored.

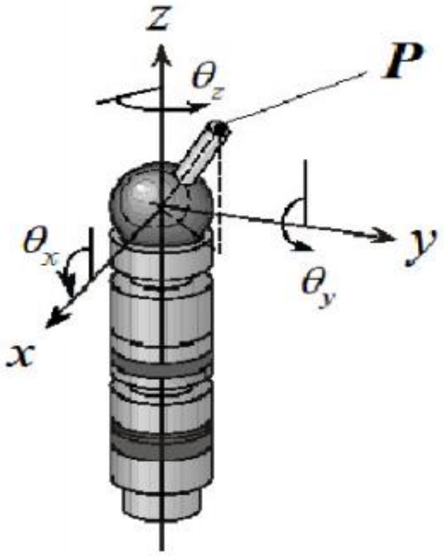


Fig. 50. Structure of ultrasonic actuator [168]

Modelling and Control

The nonlinear hysteresis model of SMA actuators has been addressed in different research [169-171]. There are two distinct categories of models to capture the hysteretic characteristics namely differential-based models which use differential equations to characterize hysteresis and operator-based models which use operators to characterize hysteresis [169]. The former one is far from easy for using in control problems since the incomplete understanding of underlying physical basis of hysteresis characteristics, leading the much effort in identifying the accurate model parameters. Cheikh et al. [170] extensively presented various approaches such as micromechanics, statistical physics, particle dynamics, classical plasticity, and energy principles to construct the constitutive models of SMA. By contrast, the later one takes advantage of phenomenological nature and describes the phenomena with mathematical equations. The authors in [169] recently surveyed several most well-known operator-based models as Preisach, Krasnosel'skii–Pokrovskii (KP), Prandtl–Ishlinskii (PI), and Maxwell-Slip. Although these models do not provide the insights of physical systems but they are capable of producing the same behaviours and produce the ease of control problems. Based on the different problems with various SMA actuator designs, researchers can select appropriate modelling methods for specific applications.

The different control schemes and parameter tuning approaches for SMA actuators were also surveyed in [169, 171]. While the researchers in [171] divided the SMA control methods into 4 main types which are linear, nonlinear, sensor-less, and PWM control, Vahid et al. [169] realized control problems as open-loop without using any feedbacks and close-loop control with available feedbacks during the system operation. Although linear controllers are easier and simpler in terms of construction and implementation, with the combination of tuning methods like Genetic Algorithm or Neural Network, the nonlinear controllers such as variable structure, segmented binary, sliding mode control, and back-stepping approach will yield far better results in both position and force tracking under the presence of high hysteresis and uncertainties in SMA actuators.

Advantages and Disadvantages

Thanks to many excellent technical properties like high corrosion resistance, bio-compatible, and non-magnetic [149], SMA actuators have been selected for numerous biomedical applications. Apart from this, research work has shown that SMA offers very high work density, high strength, significant displacement, and large force. For example, for SASI system [161], it can provide up to 30N with small size and is able to act in three-dimensional manners (extension, bending, and twisting). In addition, as given in aforementioned review, the diversity of actuator shapes (cable, spring, plate, tube, and ring) for SMA is another benefit. However, some limitations including relative small strain, low actuation frequency, and difficulty in accurate control problems are much more challenging in the use of SMA. For example, the applied current to create high temperature transformation is about 600^0C. For safety, temperature and current isolation are required for the human use. The heating and cooling methods inducing the phase transformation also have a considerable effect on the system response. According to [172], heating process can be done in several ways like conducive heat transfer, radiative heat transfer with microwaves or infrared light, inductive heating, and direct Ohmic heating. It also reported in few studies that a very high-speed response SMA actuator can be achieved by using large electrical currents. As a result, the main obstacle of the narrow bandwidth of SMA actuators is lying in the long cooling time that depends upon the size, shape, and design mechanisms of actuators. With a number of available techniques such as water immersion, heat sinking, and fluidic medium, the cooling time can be cut down. However, the heating time may grow and leakage problems must be considered. In addition, the durability and reliability of SMA actuators after experiencing multiple transformations are other challenges. Researchers have shown that the thermal effect is linked to the fatigue-life of SMA actuators which is vital for surgical applications. An overview of current smart actuators is presented in Table 3.

Table 3: Review of smart material actuated surgical devices

System	Diameter (mm)	Length (mm)	DOFs	Actuated by	Bending angle (deg)	Force (N)	Torque (N.m)	Current	Application
SASI [161]	8	250	3	SMA	60	30	-	-	MIS

Endoscope [138]	5.5	45	3	SMA	90	-	-	-	MIS
Active catheter [136]	1.4	-	4	SMA	60	-	-	80 mA	MIS
Active endoscope [173]	2	30	1	SMA	60	-	1	0.5 A	MIS
Active endoscope [157]	13	215	10	SMA	300	-	34.5	1 A	MIS
Endovascular micro-tools [156]	3	40	2	SMA	90	-	-	-	MIS
GI system [174]	15	24	2	SMA	45	-	0.5 N.mm	1.2 A	MIS
Active endoscope [175]	4	9	1	SMA	12.5	-	0.37 N.mm	0.6 A	MIS
Active catheter [137]	3.5	60	1	SMA	3	-	-	0.3 A	MIS
Active endoscope [139]	7	16	2	SMA	10.5	-	-	-	MIS
Cannula [144]	3.175	10.16	2	SMA	42	2	-	-	MIS
Multi-DOF ultrasonic motor [168]	10	31.8	3	Piezoelectric	180	-	7	-	MIS
Endoscope [147]	10	250	10	Piezoelectric	-	-	-	0.8 A	MIS

D. Magnetic Actuators

Most of transmission systems for surgical applications such as cables, fluidic actuators, and shape memory materials require “link” from power supply to drive surgical tools. Magnetic actuation uses magnetic field without requiring “link” to actuate surgical tools/joints. This type of actuator completely removes the transmission means. In surgical application using magnetic actuator as the main mode of transmission, the use of moving external permanent magnet/electromagnet to drive the internal magnet [164, 176] or MRI gradients to induce motion to ferromagnetic components [177-179] is the basic working principles. In these systems, the power and torque are magnetically transmitted from the external units through the abdominal wall into the internal units as shown in Fig. 51, leading the fact that the on-board electromagnetic motors, connection cables, and links are completely eliminated.

Various surgical applications using magnetic actuator such as laparoscopic tissue retractor [176], surgical manipulator [180], MRI-powered actuator [177], capsules [181, 182], and magnetic air capsule for painless colonoscopy [183], will be introduced and discussed in this section.

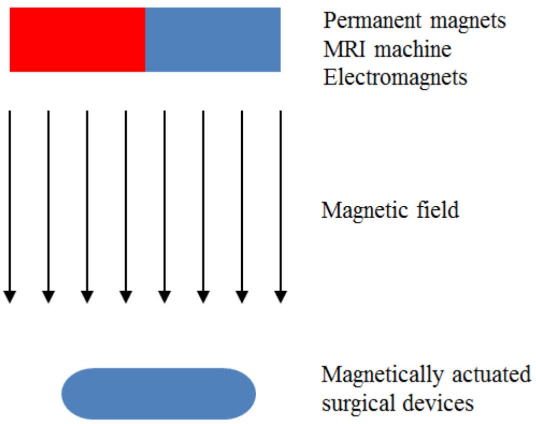


Fig. 51. The working principle of magnetically actuated surgical devices

Surgical Devices

Base on the local magnetic actuation (LMA), one single-DOF laparoscopic tissue retractor was introduced in [176]. As depicted in Fig. 52, the device consists of an anchoring unit and an actuation unit. As a supporter, the anchoring unit includes a pair of external and internal square-section permanent anchoring magnets (EAM and IAM) which stay in the abdominal wall to reinforce the stability of the system. By contrast, the actuation unit has an external driving and internal driven magnet (EDM and IDM). When a motor rotates the EDM, the IDM then also rotates, followed by the actuation of inside mechanism that is attached to IDM. The last component of this system is the offset crank mechanism that is used to produce the translational movement from the rotation of the IDM. The benchtop experiments have been conducted with the developed retractor 154mm in length, 12.5 mm in diameter, and 39.16 g in weight. The results show that it is capable of lifting more than ten times of its own weight if the abdominal thickness is 2cm.

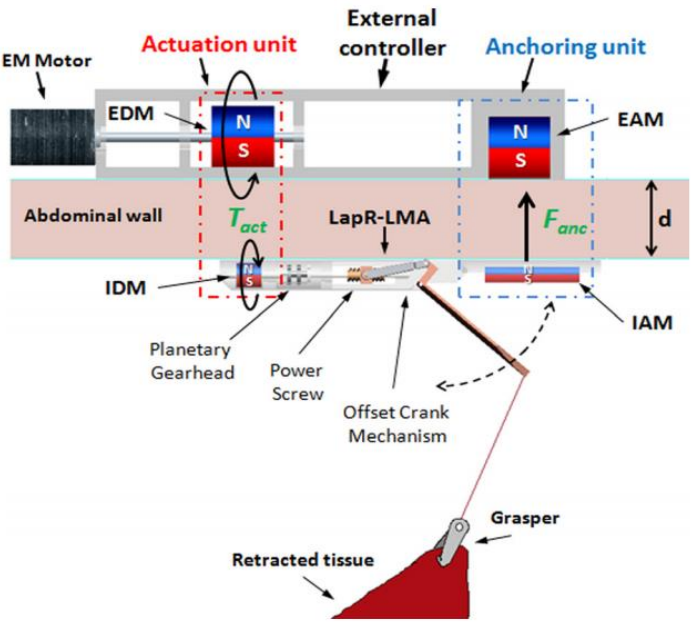


Fig. 52. The schematic representation of laparoscopic tissue retractor [176]

In a similar approach, Di Natali et al. [180] developed 4-DOFs surgical manipulator with the cable-driven spherical wrist. As shown in Fig. 53, the prototype has two modules namely actuation units and anchoring unit. The former comprises of three pairs of EDM and IDM to transmit the mechanical power from external motors to the embedded mechanisms. A set of planetary, spur gears, and antagonistic cables is utilized to actuate the 3 DOFs of articulated end effector. The latter consists of a pair of coupled permanent magnets with motorized linear side attached to the external anchoring magnets. Their main functions are to produce the supporting forces during the operation and provide the actuation the tilt angle DOF of LMA-based device. This prototype was fabricated and tested with reported attraction forces from 1N to 5 N, the torque ranged from 2 mNm to 8 mNm in a distance of 6cm between the external and internal magnets.

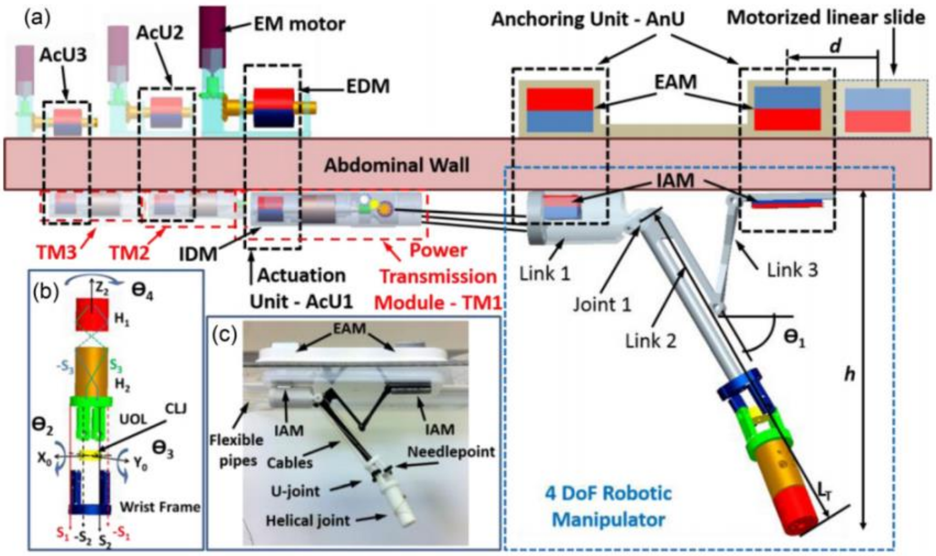


Fig. 53. LMA-based design [180]

In contrast with LMA, Vartholomeos et al. [177] presented a novel MRI-powered actuator for needle insertion in neuro-surgery.

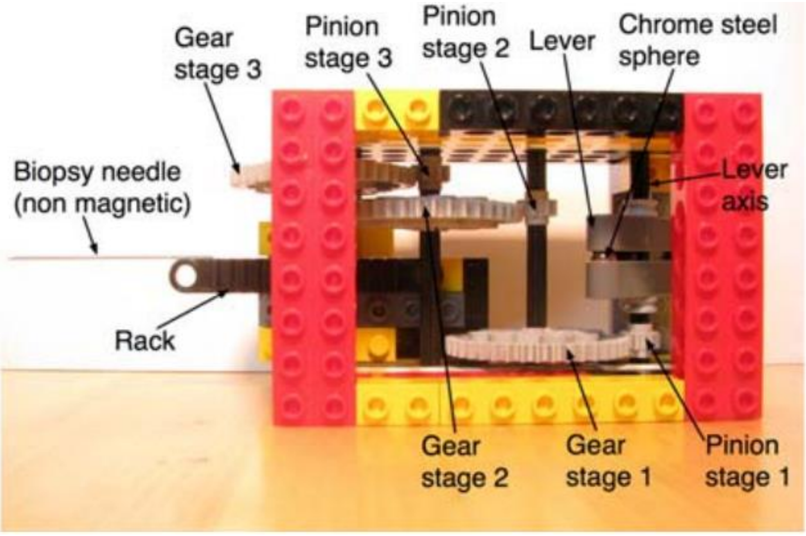


Fig. 54. MRI-powered actuator with needle design [177].

The power from the MRI machine will spin the spherical ferromagnetic particle placed in a cavity of a lever arm which is linked to a plastic gear train (Fig. 54). As a result, the rotary motion is converted into the linear motion to control the non-magnetic biopsy needle. In addition, one locking mechanism contains a bar with a pair of a ferrous steel sphere and a nonferrous steel sphere at the two ends. If the configuration is locked, the locking bar will forbid the lever from rotating. The experiments which were conducted with the prototype of 10x10x6 cm in dimension made from Legos and 1.5 T MRI Scanner demonstrated that the operation force can be generated sufficiently to puncture swine heart and the function of locking mechanism is guaranteed. The idea of using MRI gradients to drive the ferromagnetic body was also studied in some researches [178, 179, 184, 185].

External magnetic field (electromagnetic coils or permanent magnets) has been used in active locomotion systems of capsule endoscopes [164, 186, 187]. Sendoh and his co-workers [181] proposed a capsule-type magnetic actuator with fabrication and in vitro tests. The main structure of capsule consists of an inside permanent magnet and a spiral structure as shown in Fig. 55. By dint of rotating the external magnetic field, the capsule will spin and generate the propelling force due to the spiral shape to create the forward movement. A prototype with the diameter of 11mm and length 40 mm was developed and tested in-vitro with an operation speed of 1200 mm/min.

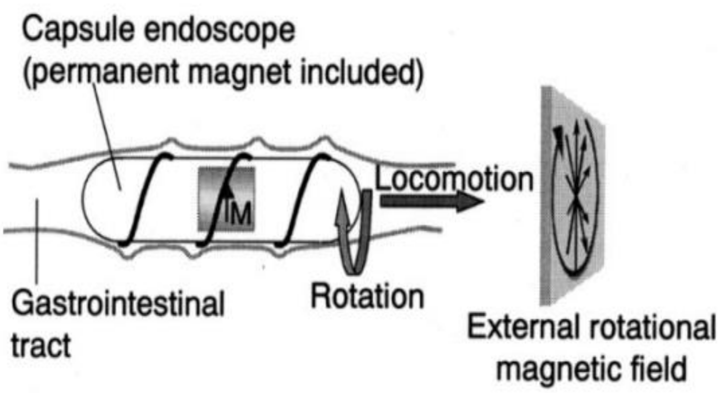


Fig. 55. Conceptual design of capsule [181]

A platform including the endoscopic device, a robotic unit, and a control box was introduced by Valdastri et al. [183]. The authors developed a magnetic air capsule (MAC) which is an endoscopic device and contains a frontal unit in the capsule shape and a multi-lumen tether. The frontal unit consists of a vision module, a permanent magnet, a magnetic sensor, and two channels for lens cleaning, and insufflation/suction/irrigation tool. To perform surgical tasks, the endoscopic tools must be placed into magnetic field generated by external magnetic actuator. Fig. 56 presents a picture of MAC with inserted biopsy forceps. The position and orientation of the robot inside the patient is controlled by the magnetic coupling in a tri-dimensional manner. The external magnet is made of NdFeB material and placed in the end-effector of a six-DOF anthropomorphic robotic arm. The validation of this design in ex-vivo and animal models gave promising results that guarantee safety requirement and function as a standard colonoscope.

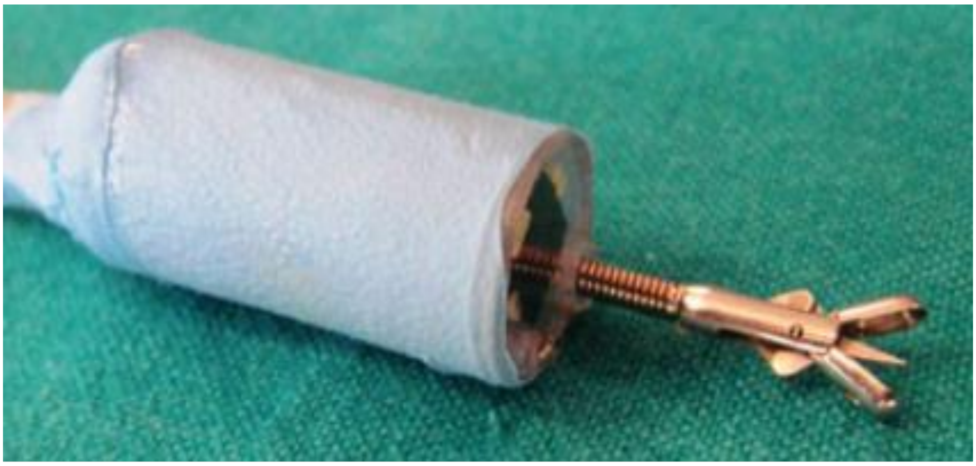


Fig. 56. The MAC with the integrated biopsy forceps [183]

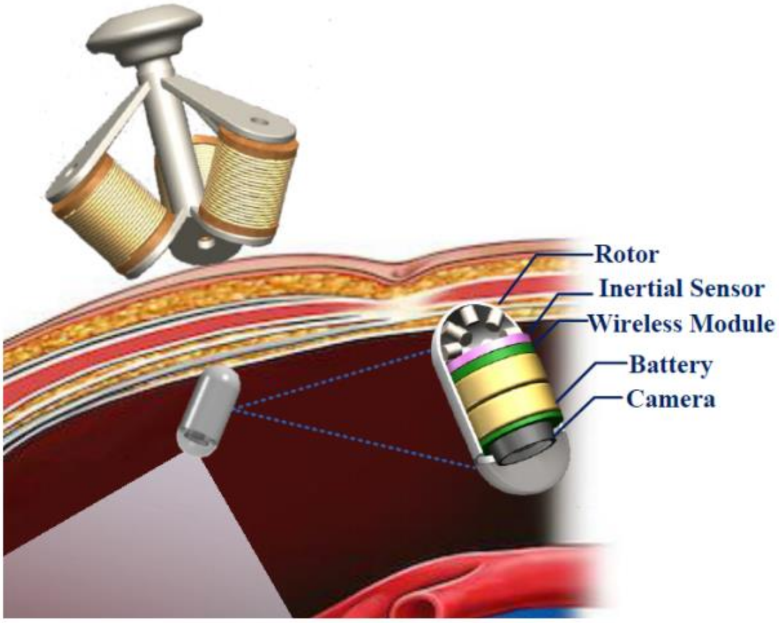


Fig. 57. The design concept of capsule-shaped camera [182]

In another approach, Xiaolong et al. [182] developed a capsule larparoscopic endoscope which consists of two main parts: a capsule-shaped camera acting as a rotor and a coil winding functioning like a stator. The coils arranged at the semi-spherical dome create a 3D rotational magnetic field to actuate and anchor the capsule during the surgical operations (see Fig. 57). A number of designs were developed for simulation and real-time experiments. The proposed mechanism demonstrated that it is capable of providing efficient force and torque to move laparoscopic camera inside the abdomen.

Modelling and Control

In order to efficiently deploy magnetic field as a power supply for actuator, the modelling and control problems play a vital role. Wang et al. [188] presented a magnetic dipole modelling approach to compute the distribution of magnetic field around the marker. After that, the Levenberg-Marquardt optimization method was exploited to calculate the position and orientation parameters. The experiments exhibit that the method is accurate and applicable for real-time tracking. Three models namely Ampere molecular current hypothesis, Dipole theory, and BiotSavart’s law are employed to analytically estimate the interaction magnetic forces and torques. Then, they are used for shape optimization and velocity control problems. In contrast, based on the theories of steady currents, permanent magnets and magnetic circuits [189], the magnetic torques and forces are gauged with finite element analysis (FEA) [176]. The authors in [190] deal with a simple model for magnetic torque and force on axial symmetric bodies while Di Natali et al. [191] propose a dynamic model for an LAM actuation unit based on coaxial magnetic gears which is then applied for closed-loop control strategies. With the given dynamic model, the load torque error is below 7.5% and the load speed error is below 2% with proposed control schemes.

Advantages and Disadvantages

An overview of current magnetically actuated medical devices is given in Table 4. As other kinds of actuators, magnetic actuators also hold both advantages and disadvantages in the surgical robotic scenario. Taking advantages into account, with the magnetic power in terms of forces and torques being wirelessly transmitted via abdominal wall, the need of connection cables or linked mechanisms is completely eliminated, followed by simpler and more lightweight systems. Otherwise, the surgical tools with high speed, capacity, and dexterity can be achieved by large-power external driving magnets or MRI machines. However, some limitations still need to be solved. For instance, the magnetic field exposes the high hysteresis, nonlinearity, and uncertainty in the models. Furthermore, since a number of coupled magnets are required for multiple-DOF systems, as a consequence, there is a presence of their interactions force, which raises the challenge in optimizing the magnet's position. Last but not least, the high-associated cost and high risk of tissue damages also need to be addressed.

Table 4: Review of magnetically actuated medical devices

System	Diameter (mm)	Length (mm)	DOFs	Actuated by	Bending angle (deg)	Force (N)	Torque (N.m)	Application
Magnetic forceps [192]	5	42	1	Magnetic field	-	-	-	Laparoscopic surgery
Tissue Retractor [176]	12.5	154	1	Permanent magnet	-	-	-	Laparoscopic surgery
LMA-based device [180]	15	-	4	Permanent magnet and cable	-	5	8 mNm	Laparoscopic surgery
Laparoscopic camera [193]	12.7	95	3	Permanent magnet	75	-	-	Laparoscopic surgery
Capsule endoscope [181]	11	30	2	Permanent magnet	-	-	3.1mNm	Laparoscopic surgery
Magnetic air capsule [183]	11	26	3	Permanent magnet	-	-	-	Laparoscopic surgery

IV. Discussion and recommendations for future works

In this review, we have outlined the development of diverse actuators for surgical applications. With the advancements of science and technology, MIS have been gradually replacing the traditional surgical procedures. With respect to actuator perspective, the difficulties related to engineering design, modelling and control, force, and position sensing still need to be addressed.

Cable-driven actuator

Taking into account of the previous limitations in the cable-routed sheath and pulley systems, there are some possible future research directions. Due to the bulkiness of the cable-pulley systems, the miniature for such systems is essential. Furthermore, the new designs to maximize the bending radius, payload, and stiffness are also significant to eliminate the fatigue problem occurred in the steel cables [87]. For the cable-conduit mechanism, the nonlinear friction force is the underlying drawbacks, leading to inefficient force applied at the distal end, backlash hysteresis and difficulty in control problem. Hence, the study of novel cable's materials and designs with the exposure of non-hysteretic characteristics, high force transmission capacity, minimal size such as polymer fibres used for fishing line and sewing thread is promising [194]. Carbon nanotube is also a potential candidate [195-202]. In addition, it is the fact that the feedback of position and force information is inevitably vital for the surgeons to do precise surgical procedures. Yet, by reason of so tiny surgical tool that the sensor attachment is impractical, it is still a hard-to-answer question. Some may propose the approach to estimate the exerted force based on the governing equations [57, 203] or the elongation of cables [59, 60]. A MEMS sensor is also a potential candidate. But, it still needs to be considered as further study.

Flexible fluidic actuator

The presence of great features such as no energized parts, high compliance and adaptability to unconstrained environments makes flexible fluidic actuators an excellent prospect in medical field. Nevertheless, such these actuators are tough to model and control, especially with the need of retaining the desired configuration without external supports. Soft material properties are unlike that of rigid. As a consequence, it is far from easy to capture them in the models, making it an unsolved challenge for researchers. Furthermore, the emergence of new soft programmable materials like bio-integrated electronics [204] or hybrid of biocompatible soft materials and tissue-engineering cells will open new opportunities for novel actuators in surgical robots.

Thanks to the extended manipulation capabilities compared to rigid robots, soft and flexible robots become an emerging trend. However, the ability to obtain higher stiffness is more challenging due to this property. Alternatively, hybrid actuator is the solution. For example, the researchers in [205] proposed a novel design concept of integrating tendon in an antagonistic way opposing the pneumatic actuation, resulting in 94% increase in stiffness. The other example was presented in [206]. In this research, the elastic modulus is greatly grown by dint of embedding polydimethylsiloxane (PDMS) with conductive propylene-based elastomer (cPBE) acting as active tendon under a certain temperature.

As shown in many studies, the information of force and position is absolutely vital in order to assist surgeons in conducting accurate surgical procedures. But, the question is still incompletely answered yet. Efficient controller is also lacked. The appearance of bio-inspired materials, for example ionic polymer metal composite and electroactive polymer artificial muscles, offers a great potential of MIS because they can work as both actuator and sensor.

Smart materials actuator

In order to effectively apply SMA actuators for surgical robots, some future research directions should be put into further consideration. Although shape memory materials (SMMs) are excellent candidates for various applications, they still hold the complexity of mathematical models and strong hysteresis nonlinearities. Then, the advancement of simple, reliable but powerful computational material models can put the control problems at ease. The development of new materials that can be composites and hybrids SMMs will be also necessary for the new actuators with larger force and stroke. Heating and cooling process play a crucial role in precisely controlling without delay. Therefore, continuous study of new heating and cooling methods as well as new, hybrid, and powerful control algorithms are essential to fully develop and apply the SMA actuators for medical field.

By combining the shape memory alloy and thermally responsive polymers, one can obtain the active variable stiffness fibres or composite actuator as shown in recent studies [207, 208]. Using flexible combination between glassy and rubbery state of polylactic acid (PLA) or acrylonitrile butandiene styrene (ABS) materials in the structure, the bending modulus of composite fibres is significantly changed. This opens a possibility to enhance the stiffness of surgical robots.

Magnetic Actuator

With the aforementioned drawbacks, we can propose some solutions for future research of magnetic actuator. For example, the developments of powerful control and model algorithms under the uncertainties, variable wall thickness, and hysteresis will result in the accurate position and orientation of the instruments. The study of novel designs with efficiency, simplicity, triangulation ability, dexterity, and low cost will open the new doors of magnetic actuator applications for surgery.

In a recent review [209], Sliker and his colleagues recommended that the use of small permanent magnetic field is better than large permanent magnetic field due to its safety issues (e.g., inadvertent attraction of instruments, electrical interference, and generation of high-strength field). For these constraints, the accurate magnetic models and closed-loop control strategies play a vital role for safe and stable interaction of magnetic field to the devices. In addition, the authors also shown that due to the limitation of working space, the localization of the device is important to precisely pose the external source. If the device location is determined correctly, the safety problem can be guaranteed to avoid accident high force contact with the patient organ.

V. Conclusion

This study serves as one of the most comprehensive review on the actuators-driven surgical robots in terms of design, modelling, control problems, and proposed potential future research directions. While there have been multiple developed categories such as cable, flexible fluidic, smart material, and magnetic actuators, every candidate still holds both disadvantages and advantages. To fully make use of robotics in surgical procedures, dedicated researches on actuators should be conducted essentially to address the current shortcomings. From authors' point of view, the precise control schemes with high hysteresis, friction force are still challenges, while the promising future directions can be realized in new materials or hybrid actuators to make them small, dexterous, and multi-functional. This review also gives the roadmap to the interested scientists and researchers in the field.

References

[1] R. A. Beasley, "Medical Robots: Current Systems and Research Directions," *Journal of Robotics,* vol. 2012, p. 14, 2012.

[2] V. Vitiello, S. L. Lee, T. P. Cundy, and G. Z. Yang, "Emerging robotic platforms for minimally invasive surgery," *IEEE Rev Biomed Eng,* vol. 6, pp. 111-26, 2013.

[3] G. S. Guthart and J. Salisbury, Jr., "The Intuitive telesurgery system: overview and application," in *IEEE International Conference on Robotics and Automation, 2000, (ICRA '00).* 2000, pp. 618-621.

[4] M. J. H. Lum, D. C. W. Friedman, G. Sankaranarayanan, H. King, K. Fodero, R. Leuschke*, et al.*, "The RAVEN: Design and Validation of a Telesurgery System," *The International Journal of Robotics Research,* vol. 28, pp. 1183-1197, 2009.

[5] J. Bodner, H. Wykypiel, G. Wetscher, and T. Schmid, "First experiences with the da Vinci™ operating robot in thoracic surgery," *European Journal of Cardio-thoracic surgery,* vol. 25, pp. 844-851, 2004.

[6] A. Tewari, A. Srivasatava, and M. Menon, "A prospective comparison of radical retropubic and robot-assisted prostatectomy: experience in one institution," *BJU Int,* vol. 92, pp. 205-10, Aug 2003.

[7] S. J. Phee, A. P. Kencana, V. A. Huynh, Z. L. Sun, S. C. Low, K. Yang*, et al.*, "Design of a master and slave transluminal endoscopic robot for natural orifice transluminal endoscopic surgery," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* vol. 224, pp. 1495-1503, July 1, 2010 2010.

[8] P. J. Schuler, U. Duvvuri, D. T. Friedrich, N. Rotter, M. O. Scheithauer, and T. K. Hoffmann, "First use of a computer-assisted operator-controlled flexible endoscope for transoral surgery," *The Laryngoscope,* vol. 125, pp. 645-648, 2015.

[9] D. J. Abbott, C. Becke, R. I. Rothstein, and W. J. Peine, "Design of an endoluminal NOTES robotic system," in *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*, 2007, pp. 410-416.

[10] S. J. Bardaro and L. Swanstrom, "Development of advanced endoscopes for Natural Orifice Transluminal Endoscopic Surgery (NOTES)," *Minim Invasive Ther Allied Technol,* vol. 15, pp. 378-83, 2006.

[11] N. Suzuki, A. Hattori, K. Tanoue, S. Ieiri, K. Konishi, M. Tomikawa*, et al.*, "Scorpion Shaped Endoscopic Surgical Robot for NOTES and SPS With Augmented Reality Functions," in *Medical Imaging and Augmented Reality*. vol. 6326, H. Liao, P. J. E. Edwards, X. Pan, Y. Fan, and G.-Z. Yang, Eds., ed: Springer Berlin Heidelberg, 2010, pp. 541-550.

[12] X. Kai, R. E. Goldman, D. Jienan, P. K. Allen, D. L. Fowler, and N. Simaan, "System design of an Insertable Robotic Effector Platform for Single Port Access (SPA) Surgery," in *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*, 2009, pp. 5546-5552.

[13] T. G. Cooper, D. T. Wallace, S. Chang, S. C. Anderson, D. Williams, and S. Manzo, "Surgical tool having positively positionable tendon-actuated multi-disk wrist joint," ed: Google Patents, 2004.

[14] P. Breedveld, H. G. Stassen, D. W. Meijer, and J. J. Jakimowicz, "Manipulation in laparoscopic surgery: Overview of impeding effects and supporting aids," *Journal of Laparoendoscopic and Advanced Surgical Techniques - Part A,* vol. 9, pp. 469-480, 1999.

[15] T. L. Nguyen, T. N. Do, M. W. S. Lau, and S. J. Phee, "Modelling, Design, and Control of a Robotic Running Foot for Footwear Testing with Flexible Actuator," presented at the the 1th International Conference in Sports Science & Technology (ICSST), Singapore, 2014.

[16] A. Degani, H. Choset, A. Wolf, and M. Zenati, "Highly articulated robotic probe for minimally invasive surgery," in *Robotics and Automation, 2006. ICRA 2006. Proceedings 2006 IEEE International Conference on*, 2006, pp. 4167-4172.

[17] N. Simaan, K. Xu, A. Kapoor, W. Wei, P. Kazanzides, P. Flint*, et al.*, "Design and Integration of a Telerobotic System for Minimally Invasive Surgery of the Throat," *The International journal of robotics research,* vol. 28, pp. 1134-1153, 2009.

[18] J. Shang, C. J. Payne, J. Clark, D. P. Noonan, K.-W. Kwok, A. Darzi*, et al.*, "Design of a Multitasking Robotic Platform with Flexible Arms and Articulated Head for Minimally Invasive Surgery," *Proceedings of the ... IEEE/RSJ International Conference on Intelligent Robots and Systems. IEEE/RSJ International Conference on Intelligent Robots and Systems,* vol. 2012, pp. 1988-1993, 2012.

[19] K. Harada, K. Tsubouchi, M. G. Fujie, and T. Chiba, "Micro Manipulators for Intrauterine Fetal Surgery in an Open MRI," in *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, 2005, pp. 502-507.

[20] L. Jei Han, S. Won Ho, and K. Dong-Soo, "A modularized wire-driven overtube using tube type bending mechanism for robotic NOTES system," in *Control, Automation and Systems (ICCAS), 2013 13th International Conference on*, 2013, pp. 631-634.

[21] P. Breedveld, J. S. Sheltes, E. M. Blom, and J. E. I. Verheij, "A new, easily miniaturized steerable endoscope," *Engineering in Medicine and Biology Magazine, IEEE,* vol. 24, pp. 40-47, 2005.

[22] C. M. Rivera-Serrano, P. Johnson, B. Zubiate, R. Kuenzler, H. Choset, M. Zenati*, et al.*, "A transoral highly flexible robot: Novel technology and application," *Laryngoscope,* vol. 122, pp. 1067-71, May 2012.

[23] P. J. Johnson, C. M. R. Serrano, M. Castro, R. Kuenzler, H. Choset, S. Tully*, et al.*, "Demonstration of transoral surgery in cadaveric specimens with the medrobotics flex system," *The Laryngoscope,* vol. 123, pp. 1168-1172, 2013.

[24] S. J. Phee, S. C. Low, Z. L. Sun, K. Y. Ho, W. M. Huang, and Z. M. Thant, "Robotic system for no-scar gastrointestinal surgery," *Int J Med Robot,* vol. 4, pp. 15-22, Mar 2008.

[25] P. Y. Chiu, S. J. Phee, Z. Wang, Z. Sun, C. Poon, T. Yamamoto*, et al.*, "Feasibility of full-thickness gastric resection using master and slave transluminal endoscopic robot and closure by overstitch: a preclinical study," *Surgical Endoscopy,* vol. 28, pp. 319-324, 2014/01/01 2014.

[26] S. C. Low, "Analysis and control of tendon-sheath actuation mechanism for a novel surgical robotic system," PhD Thesis, 2009.

[27] S. Zhongsheng, B. Gang, Y. Qingjun, and W. Zuwen, "Design of a Novel Force Feedback Dataglove Based on Pneumatic Artificial Muscles," in *Mechatronics and Automation, Proceedings of the 2006 IEEE International Conference on*, 2006, pp. 968-972.

[28] M. C. Carrozza, G. Cappiello, S. Micera, B. B. Edin, L. Beccai, and C. Cipriani, "Design of a cybernetic hand for perception and action," *Biological Cybernetics,* vol. 95, pp. 629-644, 2006/12/01 2006.

[29] T. P. Luu, Y. He, S. Brown, S. Nakagome, and J. L. Contreras-Vidal, "A closed-loop brain computer interface to a virtual reality avatar: Gait adaptation to visual kinematic perturbations," *2015 International Conference on Virtual Rehabilitation Proceedings (ICVR),* pp. 30-37, 9-12 June 2015 2015.

[30] Z. Li and R. Du, "Wire-Driven Robot Fish," in *Robot Fish*, R. Du, Z. Li, K. Youcef-Toumi, and P. Valdivia y Alvarado, Eds., ed: Springer Berlin Heidelberg, 2015, pp. 51-92.

[31] M. Hiller, S. Fang, S. Mielczarek, R. Verhoeven, and D. Franitza, "Design, analysis and realization of tendon-based parallel manipulators," *Mechanism and Machine Theory,* vol. 40, pp. 429-445, 4// 2005.

[32] C. H. Yeow, A. T. Baisch, S. G. Talbot, and C. J. Walsh, "Cable-Driven Finger Exercise Device With Extension Return Springs for Recreating Standard Therapy Exercises," *Journal of Medical Devices,* vol. 8, pp. 014502-014502, 2013.

[33] B. Bardou, P. Zanne, F. Nageotte, and M. de Mathelin, "Control of a multiple sections flexible endoscopic system," in *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, 2010, pp. 2345-2350.

[34] S. C. Jacobsen, H. Ko, E. K. Iversen, and C. C. Davis, "Control strategies for tendon-driven manipulators," *Control Systems Magazine, IEEE,* vol. 10, pp. 23-28, 1990.

[35] W. T. Latt, T. P. Luu, C. Kuah, and A. W. Tech, "Towards an Upper-limb Exoskeleton System for Assistance in Activities of Daily Living (ADLs)," presented at the Proceedings of the international Convention on Rehabilitation Engineering & Assistive Technology, ITE College East, Singapore, 2015.

[36] T. P. Luu, H. B. Lim, X. Qu, K. H. Hoon, and K. H. Low, "Subject-specific lower limb waveforms planning via artificial neural network," *2011 IEEE International Conference on Rehabilitation Robotics (ICORR),* pp. 1-6, June 29 2011-July 1 2011 2011.

[37] G. Gongliang, W. A. Gruver, and X. Qian, "A robotic hand mechanism with rotating fingertips and motor-tendon actuation," in *Systems, Man, and Cybernetics, 1991. 'Decision Aiding for Complex Systems, Conference Proceedings., 1991 IEEE International Conference on*, 1991, pp. 1023-1028 vol.2.

[38] T. P. Luu, H. B. Lim, K. H. Hoon, X. Qu, and K. H. Low, "Subject-specific gait parameters prediction for robotic gait rehabilitation via generalized regression neural network," *011 IEEE International Conference on Robotics and Biomimetics (ROBIO),* pp. 914-919, 7-11 Dec. 2011 2011.

[39] T. P. Luu, H. B. Lim, X. Qu, and K. H. Low, "Subject tailored gait pattern planning for robotic gait rehabilitation," *2010 IEEE International Conference on Robotics and Biomimetics (ROBIO),* pp. pp. 259-264, 14-18 Dec. 2010 2010.

[40] S. Thielmann, U. Seibold, R. Haslinger, G. Passig, T. Bahls, J. S*, et al.*, "MICA - A new generation of versatile instruments in robotic surgery," in *Intelligent Robots and Systems (IROS), 2010 IEEE/RSJ International Conference on*, 2010, pp. 871-878.

[41] U. Seibold, B. Kuebler, and G. Hirzinger, *Prototypic force feedback instrument for minimally invasive robotic surgery*: INTECH Open Access Publisher, 2008.

[42] M. Piccigallo, U. Scarfogliero, C. Quaglia, G. Petroni, P. Valdastri, A. Menciassi*, et al.*, "Design of a novel bimanual robotic system for single-port laparoscopy," *Mechatronics, IEEE/ASME Transactions on,* vol. 15, pp. 871-878, 2010.

[43] M. Piccigallo, F. Focacci, O. Tonet, G. Megali, C. Quaglia, and P. Dario, "Hand-held robotic instrument for dextrous laparoscopic interventions," *The International Journal of Medical Robotics and Computer Assisted Surgery,* vol. 4, pp. 331-338, 2008.

[44] Y. H. Kim, Y. J. Park, H. In, C. W. Jeong, and K. J. Cho, "Design Concept of Hybrid Instrument for Laparoscopic Surgery and Its Verification Using Scale Model Test," *IEEE/ASME Transactions on Mechatronics,* vol. 21, pp. 142-153, 2016.

[45] I. Surgical. (11 November). *davinci_surgical_system*. Available: http://www.intuitivesurgical.com/products/davinci_surgical_system/

[46] C. W. Jeong, "Tool for minimally invasive surgery," ed: Google Patents, 2014.

[47] A. De Donno, L. Zorn, P. Zanne, F. Nageotte, and M. de Mathelin, "Introducing STRAS: A new flexible robotic system for minimally invasive surgery," in *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, 2013, pp. 1213-1220.

[48] C. Seneci, J. Shang, and G. Yang, "Design of a Bi-Manual End-Effector for an Endoscopic Surgical Robot," in *The Hamlyn Symposium on Medical Robotics*, 2014, p. 83.

[49] C. Poon, H. Yang, K. Lau, W. Xu, Y. Yam, J. Lau*, et al.*, "A Bio-inspired Flexible Robot with Hybrid Actuation Mechanisms for Endoscopic Surgery," in *The Hamlyn Symposium on Medical Robotics*, 2014, p. 81.

[50] M. Remacle, M. N. P. V, G. Lawson, L. Plisson, V. Bachy, and S. Van der Vorst, "Transoral robotic surgery (TORS) with the Medrobotics Flex System: first surgical application on humans," *Eur Arch Otorhinolaryngol,* vol. 272, pp. 1451-5, Jun 2015.

[51] K.-Y. Ho, S. J. Phee, A. Shabbir, S. C. Low, V. A. Huynh, A. P. Kencana*, et al.*, "Endoscopic submucosal dissection of gastric lesions by using a Master and Slave Transluminal Endoscopic Robot (MASTER)," *Gastrointestinal endoscopy,* vol. 72, pp. 593-599, 2010.

[52] B. Dallemagne and J. Marescaux, "The ANUBIS project," *Minim Invasive Ther Allied Technol,* vol. 19, pp. 257-61, Oct 2010.

[53] S. Can, B. Jensen, E. Dean-Leon, C. Staub, A. Knoll, A. Fiolka*, et al.*, "Kinematics, control and workspace analysis of a bowden wire actuated manipulator for minimally invasive single-port surgery," in *Robotics and Biomimetics (ROBIO), 2012 IEEE International Conference on*, 2012, pp. 848-853.

[54] D. B. Camarillo, C. F. Milne, C. R. Carlson, M. R. Zinn, and J. K. Salisbury, "Mechanics Modeling of Tendon-Driven Continuum Manipulators," *Robotics, IEEE Transactions on,* vol. 24, pp. 1262-1273, 2008.

[55] B. L. Conrad and M. R. Zinn, "Interleaved continuum-rigid manipulation approach: Development and functional evaluation of a clinical scale manipulator," in *Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on*, 2014, pp. 4290-4296.

[56] J. Burgner-Kahrs, D. C. Rucker, and H. Choset, "Continuum Robots for Medical Applications: A Survey," *Robotics, IEEE Transactions on,* vol. PP, pp. 1-20, 2015.

[57] C. Kim, M. Lee, R. Wicker, and S.-M. Yoon, "Dynamic modeling of coupled tendon-driven system for surgical robot instrument," *International Journal of Precision Engineering and Manufacturing,* vol. 15, pp. 2077-2084, 2014/10/01 2014.

[58] G. M. Prisco and M. Bergamasco, "Dynamic modelling of a class of tendon driven manipulators," in *Advanced Robotics, 1997. ICAR '97. Proceedings., 8th International Conference on*, 1997, pp. 893-899.

[59] C. Low Soon, J. Phee Soo, P. Valdastri, A. Menciassi, and P. Dario, "Tendon sheath analysis for estimation of distal end force and elongation," in *Advanced Intelligent Mechatronics, 2009. AIM 2009. IEEE/ASME International Conference on*, 2009, pp. 332-337.

[60] S. J. Phee, S. Low, P. Dario, and A. Menciassi, "Tendon sheath analysis for estimation of distal end force and elongation for sensorless distal end," *Robotica,* vol. 28, pp. 1073-1082, 2010.

[61] G. Palli, G. Borghesan, and C. Melchiorri, "Modeling, Identification, and Control of Tendon-Based Actuation Systems," *IEEE Transactions on Robotics,* vol. 28, pp. 277-290, 2012.

[62] G. Palli, G. Borghesan, and C. Melchiorri, "Tendon-based transmission systems for robotic devices: Models and control algorithms," 2009, pp. 4063-4068.

[63] V. Agrawal, W. J. Peine, and B. Yao, "Modeling of Transmission Characteristics Across a Cable-Conduit System," *IEEE Transactions on Robotics,* vol. 26, pp. 914-924, 2010.

[64] V. Agrawal, W. J. Peine, B. Yao, and S. Choi, "Control of cable actuated devices using smooth backlash inverse," in *IEEE International Conference on Robotics and Automation (ICRA)*, Anchorage, AK, 2010, pp. 1074-1079.

[65] T. N. Do, T. E. T. Seah, K. Y. Ho, and S. J. Phee, "Correction: Development and Testing of a Magnetically Actuated Capsule Endoscopy for Obesity Treatment," *PLoS ONE,* vol. 11, p. e0151711, 2016.

[66] T. N. Do, T. E. T. Seah, and S. J. Phee, "Design and Control of a Novel Mechatronic Tracheostomy Tube-Inserted Suction Catheter for Automated Tracheal Suctioning," in *the 7th IEEE International Conference on Cybernetics and Intelligent Systems (CIS) and the 7th IEEE International Conference on Robotics, Automation and Mechatronics (RAM) (CIS-RAM)*, Angkor Wat, Cambodia, 2015, pp. 228-233.

[67] T. N. Do, T. E. T. Seah, and S. J. Phee, "Design and Control of a Mechatronic Tracheostomy Tube for Automated Tracheal Suctioning," *IEEE Transactions on Biomedical Engineering,* 2015, DOI: 10.1109/TBME.2015.2491327.

[68] T. N. Do, T. E. T. Seah, H. K. Yu, and S. J. Phee, "Development and Testing of a Magnetically Actuated Capsule Endoscopy for Obesity Treatment," *PLoS ONE,* vol. 11, p. e0148035, 2016.

[69] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Nonlinear Modeling and Parameter Identification of Dynamic Friction Model in Tendon Sheath for Flexible Endoscopic Systems," *ICINCO 2013 - Proceedings of the 10th International Conference on Informatics in Control, Automation and Robotics,Reykjavik, Iceland,* vol. 2, pp. pp. 5-10, 2013.

[70] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "An investigation of friction-based tendon sheath model appropriate for control purposes," *Mechanical Systems and Signal Processing,* vol. 42, pp. 97-114, 2013.

[71] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Dynamic Friction Model for Tendon-Sheath Actuated Surgical Robots: Modelling and Stability Analysis," *The Proceedings of 3rd IFToMM International Symposium on Robotics and Mechatronics, Singapore,* pp. pp. 302-311, 2013.

[72] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Dynamic Friction-Based Force Feedback for Tendon- Sheath Mechanism in NOTES System," *International Journal of Computer and Electrical Engineering,* vol. 6, pp. 252-258, 2014.

[73] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Adaptive Control of Position Compensation for Cable-Conduit Mechanisms Used in Flexible Surgical Robots," in *ICINCO 2014 - Proceedings of the 11th International Conference on Informatics in Control, Automation and Robotics*, Vienna, Austria, 2014, pp. 110-117.

[74] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "A New Approach of Friction Model for Tendon-Sheath Actuated Surgical Systems: Nonlinear Modelling and Parameter Identification," *Mechanism and Machine Theory,* vol. 85, pp. 14-24, 2015.

[75] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Adaptive control for enhancing tracking performances of flexible tendon–sheath mechanism in natural orifice transluminal endoscopic surgery (NOTES)," *Mechatronics,* vol. 28, pp. 67-78, 2015.

[76] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Real-time enhancement of tracking performances for cable-conduit mechanisms-driven flexible robots," *Robotics and Computer-Integrated Manufacturing,* vol. 37, pp. 197-207, 2016.

[77] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Position Control of Asymmetric Nonlinearities for a Cable-Conduit Mechanism," *IEEE Transactions on Automation Science and Engineering,* 2015, DOI: 10.1109/TASE.2015.2438319.

[78] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Nonlinear friction modelling and compensation control of hysteresis phenomena for a pair of tendon-sheath actuated surgical robots," *Mechanical Systems and Signal Processing,* vol. 60, pp. 770-784, 2015.

[79] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Enhanced performances for cable-driven flexible robotic systems with asymmetric backlash profile," in *Technologies for Practical Robot Applications (TePRA), 2015 IEEE International Conference on*, 2015, pp. 1-6.

[80] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Adaptive Tracking Approach of Flexible Cable Conduit-Actuated NOTES Systems for Early Gastric Cancer Treatments," in *Informatics in Control, Automation and Robotics: 11th International Conference, ICINCO 2014 Vienna, Austria, September 2–4, 2014 Revised Selected Papers*, J. Filipe, O. Gusikhin, K. Madani, and J. Sasiadek, Eds., ed Cham: Springer International Publishing, 2016, pp. 79-97.

[81] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, T. Yamamoto, and S. J. Phee, "Hysteresis modeling and position control of tendon-sheath mechanism in flexible endoscopic systems," *Mechatronics,* vol. 24, pp. 12-22, 2014.

[82] B. Conrad and M. Zinn, "Closed loop task space control of an interleaved continuum-rigid manipulator," in *Robotics and Automation (ICRA), 2015 IEEE International Conference on*, 2015, pp. 1743-1750.

[83] T. P. Luu, K. H. Low, X. Qu, H. B. Lim, and K. H. Hoon, "An individual-specific gait pattern prediction model based on generalized regression neural networks," *Gait & Posture,* vol. 39, pp. 443-448, 1// 2014.

[84] H. B. Lim, T. P. Luu, K. H. Hoon, X. Qu, A. Tow, and K. H. Low, "Study of body weight shifting on robotic assisted gait rehabilitation with NaTUre-gaits," *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS),* pp. pp. 4923-4928, 25-30 Sept. 2011 2011.

[85] T. P. Luu, H. B. Lim, X. Qu, and K. H. Low, "Pelvic motion assistance of NaTUre-gaits with adaptive body weight support," *2011 8th Asian Control Conference (ASCC),* pp. pp. 950-955, 15-18 May 2011 2011.

[86] T. P. Luu, K. H. Low, X. Qu, H. B. Lim, and K. H. Hoon, "Hardware Development and Locomotion Control Strategy for an Over-Ground Gait Trainer: NaTUre-Gaits," *IEEE Journal of Translational Engineering in Health and Medicine,* vol. 2, pp. 1-9, 2014.

[87] F. Jelínek, R. Pessers, and P. Breedveld, "DragonFlex Smart Steerable Laparoscopic Instrument," *Journal of Medical Devices,* vol. 8, pp. 015001-015001, 2014.

[88] T. N. Do, T. Tjahjowidodo, M. W. S. Lau, and S. J. Phee, "Adaptive control of position compensation for Cable-Conduit Mechanisms used in flexible surgical robots," in *Informatics in Control, Automation and Robotics (ICINCO), 2014 11th International Conference on*, 2014, pp. 110-117.

[89] V. Michaël De and R. Dominiek, "Pneumatic and hydraulic microactuators: a review," *Journal of Micromechanics and Microengineering,* vol. 20, p. 043001, 2010.

[90] A. De Greef, P. Lambert, and A. Delchambre, "Towards flexible medical instruments: Review of flexible fluidic actuators," *Precision Engineering,* vol. 33, pp. 311-321, 2009.

[91] M. De Volder, A. J. M. Moers, and D. Reynaerts, "Fabrication and control of miniature McKibben actuators," *Sensors and Actuators A: Physical,* vol. 166, pp. 111-116, 3// 2011.

[92] M. Cianchetti, T. Ranzani, G. Gerboni, I. De Falco, C. Laschi, and A. Menciassi, "STIFF-FLOP surgical manipulator: Mechanical design and experimental characterization of the single module," in *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*, 2013, pp. 3576-3581.

[93] G. Gerboni, T. Ranzani, A. Diodato, G. Ciuti, M. Cianchetti, and A. Menciassi, "Modular soft mechatronic manipulator for minimally invasive surgery (MIS): overall architecture and development of a fully integrated soft module," *Meccanica,* vol. 50, pp. 2865-2878, 2015.

[94] Y. Bailly and Y. Amirat, "Modeling and Control of a Hybrid Continuum Active Catheter for Aortic Aneurysm Treatment," in *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, 2005, pp. 924-929.

[95] Y. Haga, Y. Muyari, T. Mineta, T. Matsunaga, H. Akahori, and M. Esashi, "Small diameter hydraulic active bending catheter using laser processed super elastic alloy and silicone rubber tube," in *Microtechnology in Medicine and Biology, 2005. 3rd IEEE/EMBS Special Topic Conference on*, 2005, pp. 245-248.

[96] T. Seto and K. Takagi, "Pump-integrated flexible actuator," ed: Google Patents, 2004.

[97] A. Ruzzu, K. Bade, J. Fahrenberg, and D. Maas, "Positioning system for catheter tips based on an active microvalve system," *Journal of Micromechanics and Microengineering,* vol. 8, p. 161, 1998.

[98] N. V. Vasilyev, A. H. Gosline, A. Veeramani, M. T. Wu, G. P. Schmitz, R. T. Chen*, et al.*, "Tissue removal inside the beating heart using a robotically delivered metal MEMS tool," *The International Journal of Robotics Research,* September 4, 2014 2014.

[99] K. Eastwood, T. Looi, H. Naguib, and J. Drake, "Fluidic Actuators for Minimally Invasive Neurosurgical Instruments," in *The Hamlyn Symposium on Medical Robotics*, 2014, p. 75.

[100] M. Matsuo, K. Iijima, T. Matsunaga, and Y. Haga, "Development of hood with hydraulically variable tip diameter for endoscopic submucosal dissection," *Sensors and Actuators A: Physical,* vol. 232, pp. 267-275, 8/1/ 2015.

[101] U. Hagn, R. Konietschke, A. Tobergte, M. Nickl, S. Jörg, B. Kübler*, et al.*, "DLR MiroSurge: a versatile system for research in endoscopic telesurgery," *International Journal of Computer Assisted Radiology and Surgery,* vol. 5, pp. 183-193, 2010/03/01 2010.

[102] G. W. Dachs and W. J. Peine, "A Novel Surgical Robot Design: Minimizing the Operating Envelope Within the Sterile Field," in *Engineering in Medicine and Biology Society, 2006. EMBS '06. 28th Annual International Conference of the IEEE*, 2006, pp. 1505-1508.

[103] S. Ho-Seok, C. Jong-Ha, K. Ki-Young, and L. Jung-Ju, "The Development of human-arm like manipulator for Laparoscopic Surgery with Force sensing," in *Industrial Technology, 2006. ICIT 2006. IEEE International Conference on*, 2006, pp. 1258-1262.

[104] M. Hashizume, T. Yasunaga, K. Tanoue, S. Ieiri, K. Konishi, K. Kishi*, et al.*, "New real-time MR image-guided surgical robotic system for minimally invasive precision surgery," *International Journal of Computer Assisted Radiology and Surgery,* vol. 2, pp. 317-325, 2008/04/01 2008.

[105] T. Ota, A. Degani, B. Zubiate, A. Wolf, H. Choset, D. Schwartzman*, et al.*, "Epicardial Atrial Ablation Using a Novel Articulated Robotic Medical Probe Via a Percutaneous Subxiphoid Approach," *Innovations (Philadelphia, Pa.),* vol. 1, pp. 335-340, 2006.

[106] S. Can, C. Staub, A. Knoll, A. Fiolka, A. Schneider, and H. Feussner, "Design, development and evaluation of a highly versatile robot platform for minimally invasive single-port surgery," in *Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on*, 2012, pp. 817-822.

[107] K. Suzumori, S. Iikura, and H. Tanaka, "Development of flexible microactuator and its applications to robotic mechanisms," in *Robotics and Automation, 1991. Proceedings., 1991 IEEE International Conference on*, 1991, pp. 1622-1627 vol.2.

[108] K. Suzumori, "Elastic materials producing compliant robots," *Robotics and Autonomous Systems,* vol. 18, pp. 135-140, 7// 1996.

[109] K. Suzumori, A. Koga, and H. Riyoko, "Microfabrication of integrated FMAS using stereo lithography," in *Micro Electro Mechanical Systems, 1994, MEMS '94, Proceedings, IEEE Workshop on*, 1994, pp. 136-141.

[110] K. Suzumori, T. Maeda, H. Wantabe, and T. Hisada, "Fiberless flexible microactuator designed by finite-element method," *Mechatronics, IEEE/ASME Transactions on,* vol. 2, pp. 281-286, 1997.

[111] R. H. Gaylord, "Fluid actuated motor system and stroking device," ed: Google Patents, 1958.

[112] A. J. Moers, M. F. De Volder, and D. Reynaerts, "Integrated high pressure microhydraulic actuation and control for surgical instruments," *Biomed Microdevices,* vol. 14, pp. 699-708, Aug 2012.

[113] T. Ranzani, G. Gerboni, M. Cianchetti, and A. Menciassi, "A bioinspired soft manipulator for minimally invasive surgery," *Bioinspir Biomim,* vol. 10, p. 035008, Jun 2015.

[114] T. J. Smrt, "Animation method and device," ed: Google Patents, 1994.

[115] Bertetto AM and R. M, "A novel fluidic bellows manipulator," *J Robot Mechatron,* vol. 13, pp. 17-22, 2001.

[116] K. Negishi and T. Sato, "Bendable actuator," ed: Google Patents, 1992.

[117] F. Kawai, P. Cusin, and S. Konishi, "Thin flexible end-effector using pneumatic balloon actuator," in *Micro Electro Mechanical Systems, 2000. MEMS 2000. The Thirteenth Annual International Conference on*, 2000, pp. 391-396.

[118] C. Benjamin Che-Ming, B. John, V. Manu, M. Carlo, and M. Parameswaran, "Bending fluidic actuator for smart structures," *Smart Materials and Structures,* vol. 20, p. 035012, 2011.

[119] C. Benjamin, C. Allison, N. Nastaran, and M. Carlo, "A spatial bending fluidic actuator: fabrication and quasi-static characteristics," *Smart Materials and Structures,* vol. 21, p. 045008, 2012.

[120] Y. Shapiro, A. Wolf, and K. Gabor, "Bi-bellows: Pneumatic bending actuator," *Sensors and Actuators A: Physical,* vol. 167, pp. 484-494, 6// 2011.

[121] M. Matsuo, K. Abe, S. Suda, T. Matsunaga, and Y. Haga, "Micro hydraulic bending actuator for minimally invasive medical device," in *Solid-State Sensors, Actuators and Microsystems (TRANSDUCERS & EUROSENSORS XXVII), 2013 Transducers & Eurosensors XXVII: The 17th International Conference on*, 2013, pp. 1440-1443.

[122] M. Lazeroms, A. La Haye, W. Sjoerdsma, W. Schreurs, W. Jongkind, G. Honderd*, et al.*, "A hydraulic forceps with force-feedback for use in minimally invasive surgery," *Mechatronics,* vol. 6, pp. 437-446, 6// 1996.

[123] B.Gorissen, R. Donose, D. Reynaerts, and M. De Volder, "Flexible pneumatic micro-actuators: analysis and production," *Procedia Engineering,* vol. 25, pp. 681-684, // 2011.

[124] H. Okayasu, J. Okamoto, M. G. Fujie, and H. Iseki, "Development of a Hydraulically-driven Flexible Manipulator Including Passive Safety Method," in *Robotics and Automation, 2005. ICRA 2005. Proceedings of the 2005 IEEE International Conference on*, 2005, pp. 2890-2896.

[125] D. Rus and M. T. Tolley, "Design, fabrication and control of soft robots," *Nature,* vol. 521, pp. 467-475, 05/28/print 2015.

[126] D. Trivedi, C. D. Rahn, W. M. Kier, and I. D. Walker, "Soft robotics: Biological inspiration, state of the art, and future research," *Applied Bionics and Biomechanics,* vol. 5, pp. 99-117, 2008.

[127] R. J. Webster and B. A. Jones, "Design and Kinematic Modeling of Constant Curvature Continuum Robots: A Review," *The International Journal of Robotics Research,* June 10, 2010 2010.

[128] I. R. J. Webster, J. M. Romano, and N. J. Cowan, "Mechanics of Precurved-Tube Continuum Robots," *IEEE Transactions on Robotics,* vol. 25, pp. 67-78, 2009.

[129] A. D. Marchese and D. Rus, "Design, kinematics, and control of a soft spatial fluidic elastomer manipulator," *The International Journal of Robotics Research,* October 6, 2015 2015.

[130] T. Mahl, A. E. Mayer, A. Hildebrandt, and O. Sawodny, "A variable curvature modeling approach for kinematic control of continuum manipulators," in *American Control Conference (ACC), 2013*, 2013, pp. 4945-4950.

[131] A. D. Marchese, R. Tedrake, and D. Rus, "Dynamics and trajectory optimization for a soft spatial fluidic elastomer manipulator," *The International Journal of Robotics Research,* August 21, 2015 2015.

[132] Y. Yekutieli, R. Sagiv-Zohar, R. Aharonov, Y. Engel, B. Hochner, and T. Flash, "Dynamic model of the octopus arm. I. Biomechanics of the octopus reaching movement," *J Neurophysiol,* vol. 94, pp. 1443-58, Aug 2005.

[133] I. A. Gravagne, C. D. Rahn, and I. D. Walker, "Large deflection dynamics and control for planar continuum robots," *Mechatronics, IEEE/ASME Transactions on,* vol. 8, pp. 299-307, 2003.

[134] K. Suzumori, S. Iikura, and H. Tanaka, "Flexible microactuator for miniature robots," in *Micro Electro Mechanical Systems, 1991, MEMS '91, Proceedings. An Investigation of Micro Structures, Sensors, Actuators, Machines and Robots. IEEE*, 1991, pp. 204-209.

[135] T. Chishiro, T. Ono, and S. Konishi, "Pantograph mechanism for conversion from swelling into contraction motion of pneumatic balloon actuator," in *Micro Electro Mechanical Systems (MEMS), 2013 IEEE 26th International Conference on*, 2013, pp. 532-535.

[136] Y. Haga, M. Esashi, and S. Maeda, "Bending, torsional and extending active catheter assembled using electroplating," in *Micro Electro Mechanical Systems, 2000. MEMS 2000. The Thirteenth Annual International Conference on*, 2000, pp. 181-186.

[137] T. Namazu, M. Komatsubara, H. Nagasawa, T. Miki, T. Tsurui, and S. Inoue, "Titanium-Nickel Shape Memory Alloy Spring Actuator for Forward-Looking Active Catheter," *Journal of Metallurgy,* vol. 2011, 2011.

[138] W. Makishi, T. Matunaga, Y. Haga, and M. Esashi, "Active Bending Electric Endoscope Using Shape Memory Alloy Coil Actuators," in *Biomedical Robotics and Biomechatronics, 2006. BioRob 2006. The First IEEE/RAS-EMBS International Conference on*, 2006, pp. 217-219.

[139] V. D. Sars, S. Haliyo, and J. Szewczyk, "A practical approach to the design and control of active endoscopes," *Mechatronics,* vol. 20, pp. 251-264, 2010.

[140] H. Adldoost, B. R. Jouibary, and A. Zabihollah, "Design of SMA micro-gripper for minimally invasive surgery," in *Biomedical Engineering (ICBME), 2012 19th Iranian Conference of*, 2012, pp. 97-100.

[141] Y. Xiangnan, L. Da, and G. Mingbo, "Design and research on a shape memory alloy-actuated single-port laparoscopic surgical robot," in *Mechatronics and Automation (ICMA), 2014 IEEE International Conference on*, 2014, pp. 1654-1658.

[142] M. E. Karagozler, E. Cheung, J. Kwon, and M. Sitti, "Miniature endoscopic capsule robot using biomimetic micro-patterned adhesives," in *Biomedical Robotics and Biomechatronics, 2006. BioRob 2006. The First IEEE/RAS-EMBS International Conference on*, 2006, pp. 105-111.

[143] M. Ho, A. B. McMillan, J. M. Simard, R. Gullapalli, and J. P. Desai, "Toward a Meso-Scale SMA-Actuated MRI-Compatible Neurosurgical Robot," *IEEE Transactions on Robotics,* vol. 28, pp. 213-222, 2012.

[144] E. Ayvali and J. P. Desai, "Towards a discretely actuated steerable cannula," in *Robotics and Automation (ICRA), 2012 IEEE International Conference on*, 2012, pp. 1614-1619.

[145] E. Ayvali, C.-P. Liang, M. Ho, Y. Chen, and J. P. Desai, "Towards a discretely actuated steerable cannula for diagnostic and therapeutic procedures," *The International journal of robotics research,* vol. 31, pp. 588-603, 2012.

[146] S. Park, K. Takemura, and T. Maeno, "Development of multi-DOF ultrasonic actuators for surgical tools," *한국소음진동공학회 국제학술발표논문집2003 년1 호,* pp. 3039-3046, 2003.

[147] K. Ikuta and M. Nokata, "Two-lead-wire drive for multi-micro actuators [medical micro robots]," in *Robotics and Automation, 1999. Proceedings. 1999 IEEE International Conference on*, 1999, pp. 2378-2384 vol.3.

[148] K. Ikuta, M. Nokata, and S. Aritomi, "Biomedical micro robots driven by miniature cybernetic actuator," in *Micro Electro Mechanical Systems, 1994, MEMS '94, Proceedings, IEEE Workshop on*, 1994, pp. 263-268.

[149] J. Mohd Jani, M. Leary, A. Subic, and M. A. Gibson, "A review of shape memory alloy research, applications and opportunities," *Materials & Design,* vol. 56, pp. 1078-1113, 4// 2014.

[150] L. Sun and W. M. Huang, "Nature of the multistage transformation in shape memory alloys upon heating," *Metal Science and Heat Treatment,* vol. 51, pp. 573-578, 2009/11/01 2009.

[151] I. Mihálcz, "Fundamental characteristics and design method for nickel-titanium shape memory alloy," *Mechanical Engineering,* vol. 45, pp. 75-86, 2001.

[152] N. B. Morgan, "Medical shape memory alloy applications—the market and its products," *Materials Science and Engineering: A,* vol. 378, pp. 16-23, 7/25/ 2004.

[153] M. Sreekumar, T. Nagarajan, M. Singaperumal, M. Zoppi, and R. Molfino, "Critical review of current trends in shape memory alloy actuators for intelligent robots," *Industrial Robot: An International Journal,* vol. 34, pp. 285-294, 2007.

[154] L. Petrini and F. Migliavacca, "Biomedical Applications of Shape Memory Alloys," *Journal of Metallurgy,* vol. 2011, 2011.

[155] D. J. Hartl and D. C. Lagoudas, "Aerospace applications of shape memory alloys," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering,* vol. 221, pp. 535-552, April 1, 2007 2007.

[156] J. K. Chang, S. Chung, Y. Lee, J. Park, S.-K. Lee, S. S. Yang*, et al.*, "Development of endovascular microtools," *Journal of Micromechanics and Microengineering,* vol. 12, p. 824, 2002.

[157] K. Ikuta, M. Tsukamoto, and S. Hirose, "Shape memory alloy servo actuator system with electric resistance feedback and application for active endoscope," in *Robotics and Automation, 1988. Proceedings., 1988 IEEE International Conference on*, 1988, pp. 427-430 vol.1.

[158] P. Bidaud, J. Szewczyk, N. Troisfontaine, and J.-C. Guinot, "A Distributed SMA Actuator System and Associated Self-Guiding Control Strategy for a Scalable Endoscope Steering Device," in *Romansy 13*. vol. 422, A. Morecki, G. Bianchi, and C. Rzymkowski, Eds., ed: Springer Vienna, 2000, pp. 447-455.

[159] A. T. Tung, P. Byong-Ho, A. Koolwal, B. Nelson, G. Niemeyer, and D. Liang, "Design and Fabrication of Tubular Shape Memory Alloy Actuators for Active Catheters," in *Biomedical Robotics and Biomechatronics, 2006. BioRob 2006. The First IEEE/RAS-EMBS International Conference on*, 2006, pp. 775-780.

[160] D. Sallé, F. Cepolina, and P. Bidaud, "Surgery grippers for minimally invasive heart surgery," in *IEEE International Conference on Intelligent Manipulation and Grasping (IMG), Genova, Italy, Jul*, 2004, pp. 1-2.

[161] Z. Y. Shi, D. Liu, and T. M. Wang, "A shape memory alloy-actuated surgical instrument with compact volume," *Int J Med Robot,* vol. 10, pp. 474-81, Dec 2014.

[162] S. K. Chaitanya, S. Krishna Chaitanya, and K. Dhanalakshmi, "Design and investigation of a shape memory alloy actuated gripper," *Smart Structures and Systems,* vol. 14, pp. 541-558, 2014.

[163] M. Shahriari and A. Zabihollah, "Analytical modeling of a Minimally Invasive Surgery grasper actuated by shape memory alloy wires," in *Robotics and Mechatronics (ICRoM), 2013 First RSI/ISM International Conference on*, 2013, pp. 147-151.

[164] D. Zhao, Y. Guo, and C. Peng, "Review of the active locomotion system for capsule endoscope," *Journal of biomedical engineering,* vol. 27, pp. 215-218, 2010.

[165] K. Byungkyu, L. Sunghak, P. Jong Heong, and P. Jong-Oh, "Design and fabrication of a locomotive mechanism for capsule-type endoscopes using shape memory alloys (SMAs)," *Mechatronics, IEEE/ASME Transactions on,* vol. 10, pp. 77-86, 2005.

[166] S. Gorini, M. Quirini, A. Menciassi, G. Pernorio, C. Stefanini, and P. Dario, "A Novel SMA-Based Actuator for a Legged Endoscopic Capsule," in *Biomedical Robotics and Biomechatronics, 2006. BioRob 2006. The First IEEE/RAS-EMBS International Conference on*, 2006, pp. 443-449.

[167] B. Kim, M. G. Lee, Y. P. Lee, Y. Kim, and G. Lee, "An earthworm-like micro robot using shape memory alloy actuator," *Sensors and Actuators A: Physical,* vol. 125, pp. 429-437, 1/10/ 2006.

[168] K. Takemura and T. Maeno, "Design and control of an ultrasonic motor capable of generating multi-DOF motion," *Mechatronics, IEEE/ASME Transactions on,* vol. 6, pp. 499-506, 2001.

[169] V. Hassani, T. Tjahjowidodo, and T. N. Do, "A survey on hysteresis modeling, identification and control," *Mechanical Systems and Signal Processing,* vol. 49, pp. 209-233, 2014.

[170] C. Cisse, W. Zaki, and T. Ben Zineb, "A review of constitutive models and modeling techniques for shape memory alloys," *International Journal of Plasticity,* vol. 76, pp. 244-284, 1// 2016.

[171] M. Sreekumar, M. Singaperumal, T. Nagarajan, M. Zoppi, and R. Molfino, "Recent advances in nonlinear control technologies for shape memory alloy actuators," *Journal of Zhejiang University SCIENCE A,* vol. 8, pp. 818-829, 2007.

[172] J. Qiu, J. Tani, D. Osanai, Y. Urushiyama, and D. Lewinnek, "High-speed response of SMA actuators," *International Journal of Applied Electromagnetics and Mechanics,* vol. 12, pp. 87-100, 2000.

[173] S. Maeda, K. Abe, K. Yamamoto, O. Tohyama, and H. Ito, "Active endoscope with SMA (Shape Memory Alloy) coil springs," in *Micro Electro Mechanical Systems, 1996, MEMS '96,*

Proceedings. An Investigation of Micro Structures, Sensors, Actuators, Machines and Systems. IEEE, The Ninth Annual International Workshop on, 1996, pp. 290-295.

[174] D. Reynaerts, J. Peirs, and H. Van Brussel, "Shape memory micro-actuation for a gastro-intestinal intervention system," *Sensors and Actuators A: Physical,* vol. 77, pp. 157-166, 10/12/ 1999.

[175] J. Abadie, N. Chaillet, and C. Lexcellent, "Modeling of a new SMA Microactuator for active endoscopy applications," in *12th IFAC Symposium on Information Control Problems in Manufacturing, INCOM'06.*, 2006, pp. 161-166.

[176] N. Garbin, C. Di Natali, J. Buzzi, E. De Momi, and P. Valdastri, "Laparoscopic Tissue Retractor Based on Local Magnetic Actuation," *Journal of Medical Devices,* vol. 9, pp. 011005-011005, 2015.

[177] P. Vartholomeos, L. Qin, and P. E. Dupont, "MRI-powered actuators for robotic interventions," in *Intelligent Robots and Systems (IROS), 2011 IEEE/RSJ International Conference on*, 2011, pp. 4508-4515.

[178] S. Martel, O. Felfoul, J.-B. Mathieu, A. Chanu, S. Tamaz, M. Mohammadi*, et al.*, "MRI-based Medical Nanorobotic Platform for the Control of Magnetic Nanoparticles and Flagellated Bacteria for Target Interventions in Human Capillaries," *The International Journal of Robotics Research,* vol. 28, pp. 1169-1182, September 1, 2009 2009.

[179] S. Martel, J.-B. Mathieu, O. Felfoul, A. Chanu, E. Aboussouan, S. Tamaz*, et al.*, "Automatic navigation of an untethered device in the artery of a living animal using a conventional clinical magnetic resonance imaging system," *Applied Physics Letters,* vol. 90, p. 114105, 2007.

[180] C. Di Natali, A. Mohammadi, D. Oetomo, and P. Valdastri, "Surgical Robotic Manipulator Based on Local Magnetic Actuation1," *Journal of Medical Devices,* vol. 9, pp. 030936-030936, 2015.

[181] M. Sendoh, K. Ishiyama, and K. I. Arai, "Fabrication of magnetic actuator for use in a capsule endoscope," *Magnetics, IEEE Transactions on,* vol. 39, pp. 3232-3234, 2003.

[182] L. Xiaolong, G. J. Mancini, and T. Jindong, "Design of a unified active locomotion mechanism for a capsule-shaped laparoscopic camera system," in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*, 2014, pp. 2449-2456.

[183] P. Valdastri, G. Ciuti, A. Verbeni, A. Menciassi, P. Dario, A. Arezzo*, et al.*, "Magnetic air capsule robotic system: proof of concept of a novel approach for painless colonoscopy," *Surgical Endoscopy,* vol. 26, pp. 1238-1246, 2011.

[184] L. Arcese, M. Fruchard, and A. Ferreira, "Nonlinear modeling and robust controller-observer for a magnetic microrobot in a fluidic environment using MRI gradients," in *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on*, 2009, pp. 534-539.

[185] A. Becker, O. Felfoul, and P. E. Dupont, "Simultaneously powering and controlling many actuators with a clinical MRI scanner," in *Intelligent Robots and Systems (IROS 2014), 2014 IEEE/RSJ International Conference on*, 2014, pp. 2017-2023.

[186] L. Lejie, S. Towfighian, and A. Hila, "A Review of Locomotion Systems for Capsule Endoscopy," *Biomedical Engineering, IEEE Reviews in,* vol. 8, pp. 138-151, 2015.

[187] J. L. Toennies, G. Tortora, M. Simi, P. Valdastri, and R. Webster, "Swallowable medical devices for diagnosis and surgery: the state of the art," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science,* vol. 224, pp. 1397-1414, 2010.

[188] X. Wang and M. Q.-H. Meng, "Application of a magnetic dipole modelling approach to the problem of tracking a capsule endoscope," *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine,* vol. 225, pp. 377-387, April 1, 2011 2011.

[189] E. P. Furlani, *Permanent magnet and electromechanical devices: materials, analysis, and applications*: Academic Press, 2001.

[190] J. J. Abbott, O. Ergeneman, M. P. Kummer, A. M. Hirt, and B. J. Nelson, "Modeling Magnetic Torque and Force for Controlled Manipulation of Soft-Magnetic Bodies," *Robotics, IEEE Transactions on,* vol. 23, pp. 1247-1252, 2007.

[191] C. Di Natali, J. Buzzi, N. Garbin, M. Beccani, and P. Valdastri, "Closed-Loop Control of Local Magnetic Actuation for Robotic Surgical Instruments," *Robotics, IEEE Transactions on,* vol. 31, pp. 143-156, 2015.

[192] G. Dominguez, L. Durand, J. Rosa, E. Danguise, C. Arozamena, and P. A. Ferraina, "Retraction and triangulation with neodymium magnetic forceps for single-port laparoscopic cholecystectomy," *Surgical Endoscopy,* vol. 23, pp. 1660-1666, 2009.

[193] M. Simi, R. Pickens, A. Menciassi, S. D. Herrell, and P. Valdastri, "Fine Tilt Tuning of a Laparoscopic Camera by Local Magnetic Actuation: Two-Port Nephrectomy Experience on Human Cadavers," *Surgical Innovation,* vol. 20, pp. 385-394, August 1, 2013 2013.

[194] C. S. Haines, M. D. Lima, N. Li, G. M. Spinks, J. Foroughi, J. D. W. Madden*, et al.*, "Artificial Muscles from Fishing Line and Sewing Thread," *Science,* vol. 343, pp. 868-872, February 21, 2014 2014.

[195] P. Liu, T. Q. Tran, Z. Fan, and H. M. Duong, "Formation mechanisms and morphological effects on multi-properties of carbon nanotube fibers and their polyimide aerogel-coated composites," *Composites Science and Technology,* vol. 117, pp. 114-120, 9/29/ 2015.

[196] H. Cheng, K. L. P. Koh, P. Liu, T. Q. Tran, and H. M. Duong, "Continuous self-assembly of carbon nanotube thin films and their composites for supercapacitors," *Colloids and Surfaces A: Physicochemical and Engineering Aspects,* vol. 481, pp. 626-632, 9/20/ 2015.

[197] T. Q. Tran, Z. Fan, P. Liu, S. M. Myint, and H. M. Duong, "Super-strong and highly conductive carbon nanotube ribbons from post-treatment methods," *Carbon,* vol. 99, pp. 407-415, 4// 2016.

[198] P. Liu, A. Lam, Z. Fan, T. Q. Tran, and H. M. Duong, "Advanced multifunctional properties of aligned carbon nanotube-epoxy thin film composites," *Materials & Design,* vol. 87, pp. 600-605, 12/15/ 2015.

[199] A. Mikhalchan, Z. Fan, T. Q. Tran, P. Liu, V. B. C. Tan, T.-E. Tay*, et al.*, "Continuous and scalable fabrication and multifunctional properties of carbon nanotube aerogels from the floating catalyst method," *Carbon,* vol. 102, pp. 409-418, 6// 2016.

[200] T. Q. Tran, Z. Fan, A. Mikhalchan, P. Liu, and H. M. Duong, "Post-Treatments for Multifunctional Property Enhancement of Carbon Nanotube Fibers from the Floating Catalyst Method," *ACS Applied Materials & Interfaces,* 2016/03/11 2016.

[201] T. Tran, P. Liu, Z. Fan, N. Ngern, and H. Duong, "Advanced Multifunctional Properties of Aligned Carbon Nanotube-Epoxy Composites from Carbon Nanotube Aerogel Method," in *APS Meeting Abstracts*, 2015, p. 17006.

[202] T. Q. Tran, Z. Fan, P. Liu, and H. M. Duong, "Advanced Morphology-controlled Manufacturing of Carbon Nanotube Fibers, Thin Films and Aerogels from Aerogel Technique," presented at the Asia Pacific Confederation of Chemical Engineering Congress 2015: APCChE 2015, incorporating CHEMECA 2015. Melbourne: Engineers Australia, 2015.

[203] W. Yuan Long, K. Yo Hwan, K. Chi Yen, and L. Min Cheol, "Application of Signal Compression into Medical Surgery robot with cable-pulley system," in *Control Automation and Systems (ICCAS), 2010 International Conference on*, 2010, pp. 1765-1768.

[204] D.-H. Kim, J. Viventi, J. J. Amsden, J. Xiao, L. Vigeland, Y.-S. Kim*, et al.*, "Dissolvable films of silk fibroin for ultrathin conformal bio-integrated electronics," *Nat Mater,* vol. 9, pp. 511-517, 06//print 2010.

[205] A. Shiva, A. Stilli, Y. Noh, A. Faragasso, I. D. Falco, G. Gerboni*, et al.*, "Tendon-Based Stiffening for a Pneumatically Actuated Soft Manipulator," *IEEE Robotics and Automation Letters,* vol. 1, pp. 632-637, 2016.

[206] S. Wanliang, D. Stuart, T. Abbas, and M. Carmel, "Rigidity-tuning conductive elastomer," *Smart Materials and Structures,* vol. 24, p. 065001, 2015.

[207] M. C. Yuen, R. A. Bilodeau, and R. K. Kramer, "Active Variable Stiffness Fibers for Multifunctional Robotic Fabrics," *IEEE Robotics and Automation Letters,* vol. 1, pp. 708-715, 2016.

[208] W. Wang, H. Rodrigue, and S.-H. Ahn, "Smart soft composite actuator with shape retention capability using embedded fusible alloy structures," *Composites Part B: Engineering,* vol. 78, pp. 507-514, 9/1/ 2015.

[209] L. Sliker, G. Ciuti, M. Rentschler, and A. Menciassi, "Magnetically driven medical devices: a review," *Expert review of medical devices,* vol. 12, pp. 737-752, 2015.